Cover Letter for hess-2017-525

Dear Prof Pechlivanidis,

I, on behalf of my co-authors, would like to thank you, reviewers and Abhishek Sharma for the efforts on the improvement of our manuscript entitled "Twenty-first century glacio-hydrological changes in the Himalayan headwater Beas river basin" (hess-2017-525). These comments are all valuable and very helpful not only for improving this paper but also beneficial for our research in general.

In response to reviewers' comments and suggestions, two ensembles of four GCMs and two new bias correction methods were used for providing the forcing for a glacio-hydrological model at new 3 * 3 km resolution (it was 10*10 in the earlier version). The glacier extent module was also added in revision and re-run with the same meteorological forcing data. All the simulations have been re-run and the results have been all updated. There were certainly a lot more simulations in the revision work and new co-authors were invited in the revision regarding the new work load: Mingxi Shen worked for the new bias correction methods and provided the meteorological forcing data, drafted sections 3.4 and 4.3 and helped with plotting Fig 6 and Fig 7; Arthur F. Lutz worked with glacier extent modelling and provided the glacier extent data, also helped with the manuscript of section 4.5; Jie Chen helped with guiding bias correction methods and manuscript of sections 3.4 and 4.3; Jingjing Li helped with interpolation of forcing data under future scenarios and also helped with plotting Figs. 8, 9 and 10. So the co-authors ranking was adjusted according to their contributions to the new version of the manuscript.

We have carefully followed these comments in making revisions. Changed parts are marked in blue text in the paper, except for language corrections, which are not marked. The point-by-point response to the comments is presented.

It did take a long time and intensive work for the revised manuscript, since more GCMs data were included, new bias correction methods were used, spatial resolution was changed from 10*10 to 3*3 km, all the results have been reproduced, etc. We would like to thank Editor's encouragement, support and patience to our work and extends submission deadline during the revision process. We hope the revised manuscript is to your satisfaction, and of course we are happy to improve it according to further comments if needed.

Looking forward to hearing from you.

With all best wishes

Yours
Lu Li
On behalf of my co-authors

View Letter

Dear Editor and reviewers:
Many thanks for the review comments that we received with respect to our paper. They have contributed to considerably improving the quality of the manuscript. We have carefully addressed the reviewers' comments and suggestions. In the revised version, **blue colored** text represents text that has been revised or relocated, including methodology of two statistical downscaling methods, two ensembles of four GCMs and glacier extent projection and all the results (Tables and Figures). Typos have been corrected. Below are our point-by-point responses to each of the reviewer's comments in blue.

COMMENTS FROM EDITORS AND REVIEWERS

Review of "Projection of future glacier and runoff change in Himalayan headwater Beas basin by using a coupled glacier and hydrological model", by Li et al., HESS

General comments

Comment #1:

The manuscript addresses a relevant topic: the impact of climate change for hydrology in Asian high mountain catchments, which supply water to the irrigated areas downstream. Although the assessment is relevant and provides new insights on climate change impacts for water resources in Himalayan catchment, I believe that some major revisions are required to make the work publishable. These are specified in the comments below.

- Reply: We thank to the reviewer for your positive evaluation on our work in general and for your professional and constructive comments detailed below.

Comment #2:

Section 3.4 on statistical downscaling requires more elaboration. See also the specific comments below.

It is unclear which precipitation input has been used for the historical period. The paper mention gauge based precipitation, which I assume has been used. In the latter part of the paper the improvement of precipitation forcing using a combination of WRF modelling and gauge data is introduced. It is however unclear if this is used in the study. To me it seems that is was not used although the authors indicate that this method yields better precipitation data. If it was not used, I suggest to redo the modelling using this improved precipitation fields.

- Reply: thank you for the comment and sorry that we failed to describe this part clear enough in the original version. Yes, the gauge precipitation was used as input for the historical period. The combined WRF and gauge precipitation was only evaluated in the experiment analysis part. In this revised manuscript, we have redone the modeling using the corrected precipitation for the historical period as baseline. In this case, we have split section 5.1 and fill it into three parts: 1) section 2.2 Data, 2) section 3.5 Precipitation correction and 3) section 4.1 Corrected precipitation and section 4.2 GSM-WASMOD model calibration and validation.

Comment #3:

The model resolution (10x10 km) seems to coarse to me for hydrological modelling of mountainous areas with large variability over short horizontal distances. I think this coarse resolution is problematic for proper simulation of melt process, which are very much dictated by elevation and lapsing of temperature fields. Besides I believe that routing will be problematic at this resolution. Since the authors mention that they have higher resolution precipitation forcing data (3x3 km), my suggestion would be to setup the whole model at that resolution.

- Reply: Thanks for the comments. We have now re-run all the simulations at 3*3 km resolution and found that the results of calibration and validation were not improved comparing with the results from 10*10 km resolution simulations. It was not a surprise because of limited gauge data that we have in the study area. According to the previous studies and analysis of the influence of interpolation and station density on gridded daily data (i.e. Dirksa et al., 1998; Hofstra et al., 2010; Xu et al., 2013), the results showed that the network density could introduce biases in the mean and variance of the grid values (i.e. precipitation and temperature) compared to those expected for the true area-averages.
  However, concerning the precision of routing, glacier revolution and smooth of discharge graph and 'step change' because of the coarse resolution, we finally decided to use the 3km simulation in the revised manuscript. All the Tables and figures are updated by the new simulation results.
  The routing method in GSM-WASMOD is called NFR routing algorithm (Gong et al., 2009, 2010). We have added those clarification and citations in the methodology part related to the model routing method.

- Dirks, K.N., Hay, J.E., Stow, C.D. and Harris, D., 1998. High-resolution studies of rainfall on Norfolk Island: Part II: Interpolation of rainfall data. *Journal of Hydrology*, *208*(3-4), pp.187-193.
- Hofstra, N., New, M. & McSweeney, C. Clim Dyn (2010) 35: 841. https://doi.org/10.1007/s00382-009-0698-1
- Xu, H., Xu, C.Y., Chen, H., Zhang, Z. and Li, L., 2013. Assessing the influence of rain gauge density and distribution on hydrological model performance in a humid region of China. *Journal of Hydrology*, *505*, pp.1-12.
- Gong L., E. Widén-Nilsson, S. Halldin, C.-Y. Xu, 2009. Large-scale runoff routing with an aggregated network-response function. Journal of Hydrology, Volume 368, Issues 1-4, Pages 237-250, doi: 10.1016/j.jhydrol.2009.02.007. Copyright 2009 by Elsevier, reprinted with permission.

Comment #4:

The two used statistical downscaling techniques yield very different climate projections although they were used to downscale the same GCM. This implies that the quality of the downscaling for at least one of the methods is questionable. Also the sudden jumps in forcing when going from the historical period to the future period are unnatural and would be smooth if the downscaling performed well. My advice is to validate both statistical downscaling methods for a historical period, then use the one that performs best for the remainder of the study, if the performance is sufficient. If the performance of the downscaling method is insufficient, another method should be used. See also the specific comments below

- Reply: Thank you for your advice. After a careful consideration of the disadvantages of perfect prognosis (PP) methods and the advantages of bias correction methods, the downscaling methods of SDSM and SVM used in the original manuscript were replaced by two bias correction methods of DBC and LOCI in the revised manuscript.
  Both SDSM and SVM are regression-based downscaling methods, which involve estimating the

statistical relationship (e.g. linear relationship for SDSM and nonlinear relationship for SVM) between large scale predictors (e.g. vorticity, mean sea-level pressure, geopotential height and relative humidity) and local or site-specific predictands (e.g. precipitation and temperature) using observed climate data. The reliability of a regression-based method relies on relationships between observed daily climate predictors and predictands. However, these relationships are usually weak, especially for daily precipitation. In addition, the regression-based method is usually incapable of downscaling precipitation occurrence and generating proper temporal structure of daily precipitation, which is critical for hydrological simulations. Moreover, the PP downscaling method establishes relationship between predictors and predictands for the historical period and then applies it to future periods. However, this relationship may not hold for the future in a changed climate. This may partly explain why there was a jump between downscaled historical and future precipitation and temperature simulation in our previous manuscript. In particular, the relationship between predictors and predictands established using reanalysis predictors are applied to GCM predictors based on an assumption that reanalysis predictors and GCM predictors are both "perfectly" simulated at the grid scale (Wilby et al., 2002; Dibike and Coulibaly, 2005; Chen et al., 2011a). While reanalysis and GCM data do share some similarities, they are completely independent. Reanalysis data aims at representing the real world, whereas GCMs operate in their own virtual world. This may further result in the jump of precipitation and temperature between historical and future period.
In our revised manuscript, the bias correction methods involve estimating a statistical relationship between a climate model variable (e.g. precipitation) and the same variable of the observations to correct the climate model outputs. The use of bias correction methods is usually considered as reasonable way to achieve physically plausible results for impact studies. Compared to PP methods, bias correction methods are relatively simple to use and negate the prerequisite of a strong relationship between local-scale variables and large scale climate model variables. Previous work indicates that statistical downscaling using GCM precipitation or temperature directly as a predictor performed much better than using other predictors.

We are now using two new statistical downscaling methods (DBC and LOCI) and have added more comprehensive validation in the results section 4.3. All the relevant parts including introduction, methodology and results have been updated in the revised manuscript.

Comment #5:

The paper now has a 'Results and Discussion' section and a 'Discussion' section. This is double and should be restructured as a 'Result and Discussion' section or a separate 'Results' and 'Discussion' section.

- Reply: Thanks for the careful review. We have corrected it and there are two parts, i.e. "Results" and "Discussion".

Comment #6:

There are many textual errors. Please have the whole text reviewed by a native English speaker before submitting the revised manuscript.

- Reply: Thank you for the comments. We have done that.

Specific comments

L14: Be more specific about 'future water change'. Do you mean changes in water availability, water resources, hydrological regimes, or a combination?

- Reply: We meant both water availability and hydrological regimes. We have clarified it in the revision.

L45-46: What is the message of this sentence? I do not understand the relation here between the importance of glacier melt and the increase in precipitation.

- Reply: Thanks. We have corrected the sentence to be “The impact of glacier melt on river flow is noteworthy in the future in the Himalaya region.”

L50: You mention ‘few studies’ but you cite only one. If there are a few, please cite them all.

- Reply: Thank you. Yes, we have added two more citations here (Li et al. 2016; Hasson et al. 2016).
- Li H, Xu C-Y, Beldring S, Tallaksen TM, Jain SK, 2016. Water Resources under Climate Change in Himalayan basins. Water Resources Management 30:843–859. DOI:10.1007/s11269-015-1194-5.
- Hasson, S.U., 2016. Future Water Availability from Hindukush-Karakoram-Himalaya upper Indus Basin under Conflicting Climate Change Scenarios. Climate 2016, Vol. 4, Page 40 4, 40. doi:10.3390/cli4030040

L79: You could add citation to (Palazzi et al., 2013), providing an overview of the variation in precipitation estimates in gridded products.

- Reply: Thanks. We have added the citation here as: “An overview of the variation in precipitation estimates of gridded products was provided by Palazzi et al. (2013), in which six gridded products are compared with simulation results from a global climate model EC-Earth despite having different resolutions.”

L88-90: Is this referring to the current study or to the cited Li et al., 2017 study?

- Reply: This is referring to the current study. We have corrected it like this: “… This high-resolution WRF model from Li et al. (2017) provides a first estimation of liquid and solid precipitation in high altitude areas, where satellite and rain gauge networks are not reliable.

L95-98: I would expect that you would answer question 3 first, because it also affects the answers to questions 1 and 2.

- Reply: We agree with reviewer’s suggestion and have changed the order of the questions as suggested: “(1) How much uncertainty is in the precipitation over the ungauged high-altitude in Beas river basin? (2) How will the future water availability change due to higher glacier melt under warmer future in Beas river basin over the Himalaya region? (3) What are the uncertainties of the future water from GCMs or Statistical downscaling methods? ”
  In this revised manuscript, we have re-run the modeling using the corrected precipitation for the historical period as baseline.

L99-105: I would not sum the sections but just describe your approach in 2 or 3 sentences: To answer these questions we use ... and ... etc.

- Reply: We have re-written this part as this: “To answer these questions, precipitations from a high-resolution WRF simulation and Gauge are investigated and a corrected precipitation is used for the hydrological simulation as the historical baseline. In the study, we use a glacio-hydrological model together with eight GCMs under two generation of scenarios, i.e. RCP 4.5 and RCP 8.5 and two statistical downscaling (SD) methods. We firstly focus on the simulation of the present day water cycle and validation of the simulated discharge by using the observed discharge. The uncertainties of the precipitation over high-altitude area and hydrological simulation are further discussed. Besides, the future climate change and glacier extent change and hydrological changes have been investigated. At last, the uncertainty from GCMs and statistical downscaling methods is analyzed and discussed before presenting the main conclusions."

L107: Mention the percentage of the basin area covered by glaciers.

- Reply: Yes, we have added it: "The study area is Beas river basin, upstream of the Pandoh Dam with a drainage area of 5406 km^2, out of which 780 km^2 (14.4%) is under permanent snow and ice".

L119: Include also the glacier outline data and glacier mass balance data you used in this section. Also mention the future climate data (the one downscaled GCM).

- Reply: Thanks. We have added those information in Data section:
  "The basin boundary in the study is delineated based on HYDRO1k (USGS, 1996a), which is derived from the GTOPO30 30-arc-second global-elevation dataset (USGS, 1996b) and has a spatial resolution of 1 km. HYDRO1k is hydrographically corrected such that local depressions are removed and basin boundaries are consistent with topographic maps. Daily precipitation of 7 rain gauge stations, daily minimum and maximum air temperature of 4 meteorological stations and daily potential evapotranspiration of one station obtained from Bhakra Beas Management Board (BBMB) in India were used for GSM-WASMOD modelling. The outlet discharge station of Thailout was used for GSM-WASMOD model calibration and evaluation, which was also obtained from the BBMB. Glacier outlines were taken from the recently published Randolph Glacier Inventory (RGI 6.0) (2017) (https://doi.org/10.7265/N5-RGI-60). The annual glacier mass balance data of Chhota Shigri Glacier that are used in the model calibration are taken from the previous studies of Berthier et al. (2007) and Vincent et al. (2013). The Beijing Climate Center Climate System Model (BCC_CSM1.1) developed at the Beijing Climate Center (BCC), China Meteorological Administration (CMA) (Wu et al., 2013) is chosen as the GCM model for use in regional statistical downscaling of future simulations. Furthermore, the daily precipitation from a horizontal 3 km WRF simulation by Li et al. (2017) is also used in the study for further experiment and discussion on the precipitation uncertainty."

L120: Add a citation for the Hydro1k dataset

- Reply: Yes. We have added it. Please see the answer above.

L123: Also show the locations of the stations where temperature and potential evapotranspiration is measured in Figure 1. Are you sure that potential evapotranspiration is measured there, or should this be actual evapotranspiration?

- Reply: Yes, we have added those 4 meteorological stations. Please see the new Figure 1 in the reply to L243-246. It is potential evaporation from Pan evaporation.

L133: Is there a specific reason you used the GLIMS dataset and not the more recent Randolph

Glacier Inventory (Arendt and 87 others, 2015)? Did you do any quality control of the GLIMS data over your basin? Given that your basin is not that large, it may be worthwhile to do your own mapping of glacier outlines using remote sensing data, if the quality of GLIMS or RGI are insufficient over your basin.

- Reply: Thanks for your comment. We have downloaded the RGI 6.0 and compared it with the data from GLIMS. The two glacier shape files have a slight difference but the glacier covered grids are identified the same as that from GLIMS. So in this case, it didn't impact the simulation results and conclusions at the end. In the revised manuscript, we have updated the glacier outlines data to be Randolph Glacier Inventory 6.0 in section 3.1: "Those glacier grid cells were defined by ESRI ArcGIS system v. 9.0 (or higher) and set up before modeling based on the glacier outlines from the RGI (6.0) (2017) (https://doi.org/10.7265/N5-RGI-60) (Berthier, 2006; Raup et al., 2007)." Please also see the answer above to the comment of L119.

L137: What is the assumption of 20% based on?

- Reply: We have clarified that this is an empirical estimate.

L142: How where these percentages for adjustments of the DDFs obtained? Has debris cover been considered in your modelling? If debris cover is present on glaciers in your basin, this will have very different melt properties (e.g. Vincent et al. 2016).

- Reply: This is an empirical estimate and we have added citations in the revised manuscript. No, the debris cover is not considered in the modeling right now. We have clarified it in the revision.

L130-144: This section requires more elaboration of the description of the GSM. Did you calculate for different elevation zones and use vertical temperature lapse rate? Or is the same elevation, temperature and precipitation used for all glaciers? If this module was used before, please provide a reference. Otherwise it will be better to write out the equations listed in Table 1 in the main text and complete describe the model.

- Reply: The GSM is calculated based on grids. In each grid cell of glacier, the input data (including elevation, temperature and precipitation) are the same. The temperature and precipitation are interpolated from stations by IDW method and the vertical temperature lapse rate is considered in the IDW method for temperature. This GSM has been used before. We added the citation here (Li et al. 2014; Engelhardt et al. 2012) and have added more description in method section of GSM:

  "A conceptual glacier- and snow- melt module (GSM) (Li et al. 2014; England et al. 2012) was used to compute glacier mass balances and melt-water runoff from the glacier in the study basin, which was only applied to the grid cells of the glacier-covered area. Those glacier grid cells were defined by ESRI ArcGIS system v. 9.0 (or higher) and set up before modeling based on the glacier outlines from the RGI (6.0) (2017) (https://doi.org/10.7265/N5-RGI-60) (Berthier, 2006; Raup et al., 2007). The gridded temperature and precipitation are interpolated based on the station data by Inverse Distance Weighted (IDW) method, in which the vertical temperature lapse rate of −6 °C km−1 is used to downscale the temperature station to the elevations of the grid cells (Kattel et al., 2013). The daily gridded temperature and precipitation were input data for the GSM module, which calculated both snow accumulation and melt-water runoff."

L148: A spatial resolution of 10 x 10 km sounds very coarse to me considering the size of the basin. I don't think you can get a sufficient representation of the changes in meteorological variables, which vary strongly over short distances in the mountains. Besides, this resolution is probably problematic to do a proper routing.

Reply: Thanks for the professional comments. Our response was presented to the General Comment #3, above. We have now re-run all the simulations on 3*3 km resolution and updated table and figures in the revised manuscript.

L150: Simply interpolation air temperature horizontally will not be sufficient for terrain with strong vertical differences. I advise to use a vertical temperature lapse rate to downscale the temperature field to the elevations of your grid cells.

- Reply: Thanks for your comment. This is actually what we did in the IDW interpolation for gridded temperature, but we didn't explain it in detail and clear enough. So we have added the information in the methodology section of the revised manuscript: "The gridded temperature and precipitation are interpolated based on the station data by Inverse Distance Weighted (IDW) method, in which the vertical temperature lapse rate of −6 °C km−1 is used to downscale the temperature station to the elevations of the grid cells (Kattel et al., 2013)."

L164: Include reference to the paper that describes the glacier change parameterization (Lutz et al., 2013).

- Reply: We have added it: "The glacier changes are the result of a close interplay of projected changes in temperature and precipitation, which are calculated monthly in the parameterization approach (Lutz et al., 2013)."

L181: I do not understand the acronym MLR for linear regression. Where does the 'M' stand for?

- Reply: Thanks for the careful review. 'M' stands for 'multiple' and MLR means the multiple linear regression. We have corrected it in the revised manuscript.

L185: the variables 'u', 'w' and 'W' need to be described. Otherwise this part is completely unclear. A few lines of description in addition to the two equations would also be useful.

- Reply: Thank you for the comment. $\hat{u}_t^i$ is the i th corresponding climatic predictor on the t th day; W_t^{sim} is the SDSM-simulated probability on the t th day; w_t^{sim} is the simulated precipitation state on the t th day. Now we have updated the corresponding description in the 3.4 section.

L188: I would not state 'superior ability of simulation' for a method that does well in transforming changes in the mean, but not the standard deviation and extremes, as stated in L181-182.

- Reply: Yes, agree. We have corrected it and updated the corresponding description in the 3.4 section.

L195 ‘l’ and ‘i’ need to be explained.

- Reply: Thanks. ‘l’ is the upper limits of the numbers of the sets{X,Y}.’i’ is an ordinal number for the vector X and Y. We have corrected it in the revised manuscript.

L198: ‘T’ needs to be explained

- Reply: Thanks. ’T’ means the transposition in the calculation. We have corrected it in the revised manuscript.

L199: What is meant by ‘the parameters’. What kind of parameters?

- Reply: Thanks for the careful review. ‘the parameters’ means in this equation, both ‘W’ and ‘b’ can be adjusted to make the equation balanced: “where W and b are the parameters which determine the shape of hyperplanes Y ”. We have updated it in the revised manuscript.

L201: subscript ‘j’ needs to be explained

- Reply: Thanks. ’j’ is also an ordinal number like, which makes X_i and X_j independent to each other. We have corrected it and made it clearer.
-

L213: Should ‘station-scale hydrological data’ be ‘station-scale meteorological data’? I cannot imagine that the downscaling is done with hydrological data.

- Reply: Yes, thanks for the carefully review. We have corrected it. Please see section 3.4.2

L213-215: Which GCMs are used?

- Reply: We have added the information of GCMs in Data section. Besides, we also re-run all the simulations with eight GCMs including both Rcp4.5 and Rcp8.5. Please see them in table 2.

L221-222: Do I understand correctly that the observed glacier mass balance at one glacier was used for calibration? Can you elaborate on the assumption that this one glacier is representative for all glaciers in the catchment? You could also compare with remote sensing data (Brun et al., 2017; Gardelle et al., 2013) to see how large the spatial variation in glacier mass balance is in your catchment, to say something about the representativeness of Chhota Shigri.

- Reply: Thanks for the references and comment. In our study area, the glaciological mass balance series published in Spiti-Lahaul region (where Beas river basin locates) that is available for comparison are the Chhota Shigri glacier and Bara Shigri glacier (Berithier et al. 2007). In which, the only one is long enough to be comparable to our simulation period is the Chhota Shigri glacier (2002-2014), which has geodetic mass balance for validation (Azam et al. 2016). We have compared the mass balance data from previous studies for the Chhota Shigri glacier. In the study of Gardelle et al. (2013), a detailed map of elevation changes during 2000-

2011 in Spiti-Lahsul region based on SPOT5 DEM is given, which showed that the changes of the glaciers in the Beas river basin are quite similar as the change in Chhota Shigri glacier in general, although there is variability both in individual glacier and over the region. So we used the mass balance data of Chhota Shigri glcier for representing all the glaciers in our small basin.
We have added this explanation in the section of Model calibration: “There is an intra-regional variability of individual glacier mass balance in High Mountain Asia (HMA) and less negative mass balance than most other estimates according to the recent study of Brun et al. (2017). From the study, the annual glacier mass balance is -0.49+/-0.2 m w.e.yr-1 in Spiti-Lahaul region (where Chhota Shigri glacier locates) during 2000-2008 based on ASTER and 0.37+/-0.09 m w.e.yr-1 in Western Himalaya region from RGI Inventory during 2000-2016 based on ASTER. Besides, a detailed map of elevation changes during 2000-2011 in Spiti-Lahsul region based on SPOT5 DEM is given in the study of Gardelle et al. (2013), which showed that the changes of the glaciers in the Beas river basin are quite similar as the changes in Chhota Shigri glacier during 2000-2011 in general, although there is variability both in independent glacier and over the region.

L233: The biases are seem to be large for June-August because of the common problem of underestimated high-altitude precipitation in gauge-based data. If you did not use the improved precipitation fields based on WRF which you discuss in section 5.1, I believe you should include a correction for that in your model. It could be an additional parameter that you calibrate in advance, to make sure that the precipitation input is at least higher than the observed discharge. Have a look at for example (Dahri et al., 2016; Immerzeel et al., 2015). I am not saying you should use an approach as in the cited studies, but at least do a correction on the precipitation input to make it more realistic.

- Reply: Thank you very much for the suggestion. We have used the corrected precipitation based on WRF and gauge for historical baseline simulation. And the same correction has also been done for the precipitation in all the future scenarios. We have updated it in the revised manuscript of both methodology and results.

L236: Fig 2 and 3 are much repetition and can be combined in one figure. How do slow flow and fast flow relate to rain-runoff? I rain-runoff surface runoff and are slow flow and fast flow both groundwater flow and flow through the soil layer?

- Reply: Thanks for the comment. We have removed Fig.3 and added more information in the results part of the revised manuscript: “In Fig 2, the total discharge includes fast-flow and slow-flow from non-glacier area and discharge from glacier area, which includes rainfall discharge, snow-melt and ice-melt discharge. The fast-flow is generally considered to be surface runoff and the slow-flow refers to base flow. ”

L241-243: I think it is a bit misleading to show one of the years where the model has best performance in figure 5 and then conclude that the model ‘worked fine’ in the study basin. You clearly indicated that there are quite large biases, especially during the high flow season, which is understandable when simulating high mountain hydrology. I would remove figure 5.

- Reply: Thanks for the suggestion. We have removed Fig. 5.

L243-246: Similar comment as for L221-222. How representative is the glacier mass balance at

Chhota Shigri for your entire catchment? Here you compare the simulated glacier mass balance for the entire catchment to the observed mass balance at one glacier.

- Reply: Thanks for the comment. Please see our reply above for L221-222.
  In our study area, the only glaciological mass balance series published are the Chhota Shigri glacier and Bara Shigri glacier (Berithier et al. 2007). In which, the only one is long enough to be comparable to our simulation period is the Chhota Shigri glacier, which has geodetic mass balance for validation (Azam et al. 2016). We have compared the mass balance data from previous studies for the Chhota Shigri glacier. In the study of Gardelle et al. (2013), a detailed map of elevation changes during 2000-2011 in Spiti-Lahsul region based on SPOT5 DEM is given, which showed that the changes of the glaciers in the Beas river basin are quite similar as the change in Chhota Shigri glacier in general, although there is variability both in independent glacier and over the region. So we used the mass balance data of Chhota Shigri glcier for representing all the glaciers in our small basin.
  In order to make it clearer in the manuscript. We have rewritten L236-237 and add the location of Chhota Shigri glacier in Fig. 1 in the revised manuscript: "In our study area, the glaciological mass balance series published in Spiti-Lahaul region (where Beas river basin locates) that is available for comparison are the Chhota Shigri glacier and Bara Shigri glacier (Berithier et al. 2007). In which, the only one is long enough to be comparable to our simulation is the Chhota Shigri glacier, which has geodetic mass balance for validation (Azam et al. 2016). The Chhota Shigri Glacier intersects with the northeast boundary of Beas river basin, which is close to Manali and Bhuter." We have updated the Fig. 1 in the revised manuscript.

Fig.6: Move the legend outside the plot or draw a clear boundary around it. Now it seems that de symbols in the legend are actual plotted values.

- Reply: Thanks. We have corrected the figure and have updated it in the revised manuscript.

Table 4: I do not understand the line below the headers (0, mean, mean, mean). I also do not understand why the column indicating the statistical downscaling method is headed 'RCM'. I also do not understand the meaning of the header 'Glacier – GCM'. I also do not understand what the line at the bottom of the table 'CMIP5: Bcc-csm' should indicate.

- Reply: Thanks for the comment. We have changed this table in order to make it clearer to read and understand. Please see Table 3 in the revised manuscript.

Table 4: You used different GCMs to generate future meteorological forcing for the hydrological model than were used for the future glacier projections. Ideally these should be the same since they are part of the same system. However, I understand that you took glacier projections from another study and included them in yours. I agree that it is better to use some glacier projection is stead of none, but you need to describe the disadvantages of the mismatch in future meteorological forcing used for the glacier evolution model and the hydrological model. This should be more elaborated than in line 300-305.

- Reply: Thank you for the comment. In order to keep consistence and have a more comprehensive future picture of water availability of Beas river basin, we have added the same two ensembles of four GCMs as the future projection of glacier in the study of Lutz et al (2016). We invited Arthur Lutz as a co-author for the revised manuscript. The same meteorological forcing was taken for re-running glacier evolution model by DR Lutz. So there is no longer mismatch in the meteorological forcing for hydrological model and for glacier evolution model in the revised manuscript.

Fig 7: In the caption you mention 'RCMs'. I do not think you can do that because you did not use

RCMs in your study, but statistically downscaled GCMs. I suggest to replace ‘RCMs’ by ‘downscaled GCMs’.

- Reply: Thanks. We have replaced “RCM” by “Statistical Downscaling methods” in the whole manuscript.

L250-254, Fig 7: The two different downscaling methods lead to very different changes. This needs explanation of the underlying reasons. I wonder why the two methods were used. I suggest to validate both downscaling methods for the historical period, select the method that performs best, then use that method for the future projections.

Reply: Please see the reply to general comment #4. We have changed the statistical downscaling methods of SDSM and SVM to BDC and LOCI, and done more comprehensive comparison of the two new bias correction methods of the DBC and LOCI. In the revised manuscript, the uncertainty related to the choice of bias correction methods has been considered by using two bias correction methods (LOCI and DBC) with different levels of complexity. LOCI and DBC representing two typical bias correction categories are both commonly used in literatures. LOCI is a mean-based bias correction, which applies a mean monthly correction factor to GCM-projected simulations for each calendar month over the future period. DBC is a distribution-based method, which corrects the empirical distribution of GCM-projected simulations for each calendar month. Both methods correct the frequency of precipitation occurrence.
We have added section 4.3 Evaluation of DBC and LOCI in the revised manuscript.

Fig9: For precipitation, there is a large mismatch between the two downscaling methods, even at the start of the future simulation. For SVM they start around 1000 mm/yr whereas for SDSM they start at around 1500 mm/yr. This means that at least one of them shows a large sudden jump going from the historical period to the future period. If the downscaling was done properly, the transition from the end of the historical period to the start of the future period should be smooth.This needs to be addressed.

- Reply: Thank you very much for the careful review. We agree that the different SD methods may result in inconsistency in the simulations. After a careful consideration of the disadvantages of perfect prognosis (PP) methods and the advantages of bias correction methods, the downscaling methods of SDSM and SVM used in the original manuscript were replaced by two bias correction methods of DBC and LOCI in the revised manuscript.

  In our revised manuscript, the bias correction methods involve estimating a statistical relationship between a climate model variable (e.g. precipitation) and the same variable of the observations to correct the climate model outputs. The use of bias correction methods is usually considered as reasonable way to achieve physically plausible results for impact studies. Compared to PP methods, bias correction methods are relatively simple to use and negate the prerequisite of a strong relationship between local-scale variables and large scale climate model variables.

  We have now done a more comprehensive validation of those two statistical downscaling methods, and have added the results section 4.3. All the relevant parts including introduction, methodology and results in the revised manuscript have been updated.

The difference in temperature projections for the SDSM and SVM method are enormous towards the end of the century. Describe the reasons for this large difference in the manuscript. Since these methods where used to downscale 1 GCM, the quality of the downscaled forcing for at least one of the downscaling approaches is questionable to me.

- Reply: Please see the reply above. We have chosen two new bias correction methods, i.e. DBC and LOCI in the revised manuscript. We have done more comprehensive validation of those two methods and added section 4.3 Evaluation of DBC and LOCI in the revised manuscript.

Table 5: The change in discharge is very negative, although you have positive changes in precipitation. It seems that it can partly be explained by the increase in evapotranspiration and by losing the additional water from the negative glacier mass balance in the future. Nevertheless, it feels to me that the decrease in total runoff cannot be that large when precipitation amounts are increasing. Please provide a check of the simulated water balance components (precipitation, evapotranspiration, ice melt, snow melt, rainfall discharge, fast flow, slow flow, and changes in storages) of the catchment for your reference and future runs in the revised manuscript.

- Reply: Thank you very much for the carefully review. We have now chosen two new statistical downscaling methods, i.e. DBC and LOCI and added two ensembles of four GCMs of Rcp4.5 and Rcp8.5 in the revised manuscript.
  There are no more issues of 'jump' between historical period and future period from the statistical downscaling. The discharge significantly decreases because of the glacier retreating. We have made the correction and have updated all the results.

Fig 12: The different lines of the ensemble member are indistinguishable. I suggest to show the ranges as a shaded area with a line for the mean. Since the figure shows all the members from Table 4, I do not understand why all precipitation projections here start around 1000 mm/yr, whereas in Figure 9 the precipitation projections show large difference for the two downscaling methods.

- Reply: Thank you very much for the suggestion and careful review. We have now chosen two new statistical downscaling methods, i.e. DBC and LOCI and added two ensembles of four GCMs of Rcp4.5 and Rcp8.5 in the revised manuscript. We have made the correction and have updated all the results. We also improved the Fig 12 according to the suggestion.

In the caption you mention that the plot shows glacier melt discharge for CanESM2. In Table 4 you indicate that 2 out of the 16 members use glacier projections for CanESM2. How come all the 16 members are shown in Figure 12? This is very unclear. It is also unclear how one could derive the in the caption mentioned tipping point years (2026 and 2052) from the plot.

- Reply: Thank you very much for the careful review. It was a typo. But we have now chosen two new statistical downscaling methods, i.e. DBC and LOCI and added two ensembles of four GCMs of Rcp4.5 and Rcp8.5 for a more comprehensive comparison and uncertainty analysis in the revised manuscript. We have updated all the results.

Glacier melt contributions around 500 mm/yr seem rather high compared to the plot you showed in Figure 2. There the annual sum of the 'Glacier ablation' seems to be much lower (around 250 mm/yr as far as I can estimate). This would also imply a sudden 'jump' going from the historical period to the future period, which is unnatural. This makes the whole story somewhat questionable. To gain confidence about the projections please provide a check of water balance components as indicated in the comment to Table 5.

- Reply: Thank you very much for the careful review. We have now chosen two new statistical downscaling methods, i.e. DBC and LOCI and added two ensembles of four GCMs of Rcp4.5 and Rcp8.5 in the revised manuscript.
  There are no more issues of 'jump' between historical period and future period from the statistical downscaling. We have updated all the results.

L306: See comment on the use of 'RCM' at Figure 7

- Reply: Yes. We have corrected it to be "statistical downscaling methods".

L308: I think you refer here to the 'jump' I point out in my comment about about the glacier melt in Figure 12. I think this is something that needs to be addressed before the projections have sufficient reliability to be published in HESS.

- Reply: Thank you for the comment. Yes, We have now chosen two new statistical downscaling methods, i.e. DBC and LOCI and added two ensembles of four GCMs of Rcp4.5 and Rcp8.5 for a more comprehensive comparison and uncertainty investigation for the future water cycle and availability in this Himalaya headwater Beas river basin.

L313-337: This part comes out of the blue. It is unclear if you used the combined precipitation and WRF forcing in this study. If you did not, I suggest you redo the study with this precipitation dataset if it has a better representation of precipitation. If you did, integrate this part then in the manuscript (i.e. the methodology to the Methods section, and the results to the Results and Discussion section).

- Reply: As we mentioned in the earlier reply, in the revised manuscript, we have redone the modeling using the corrected precipitation for both the historical period as baseline and future scenarios.

Technical comments

L11: Remove 'the' at the end of the sentence

- Done.

L13: remove 'the'. 'Climate' shoud be with lower case 'c'

- Done.

L18: remove 'impact'

- Done.

L21: Better to reword to: 'This will result in a general decrease in river runoff for all the scenarios.'

- Done.

L23: I guess you mean 'WRF precipitation projection'

- Yes, clarified.

L28: Remove the first 'The'. From here I will stop correcting the redundant use or absence of 'the'. Please have the manuscript checked by a native English speaker. It is advisable to do this before submission for any future manuscripts.

- Reply: thank you very much. We have carefully done proofreading.

L29: Reword to: 'Hydrological models have been developed and used as a main assessment tool in the Himalayan region to estimate the impacts of climate change for future water resources.'

- Done.

L35: 'the' should be 'an'. 'GCM' should be 'GCMs'.

- Done.

L38: Change 'More' to 'An increase in'

- Done.

L39: Change 'by' to 'according to'

- Done.

L54: Introduce Regional Climate Models before using the acronym RCM

- Done.

L83: 'simulations' should be 'simulation'

- Done.

L95: Reword to 'The main questions we try to answer in this study are:'

- Corrected.

L110: add m asl (metres above sea level)

- Done.

L115: correct 'meteorological'

- Done.

L137: No parentheses needed here

- Done.

L141: No parentheses needed here

- Done.

L167: ‘totally’ should be ‘in total’

- Done.

L178: Remove ‘was’ and ‘which’

- Done.

L243: Included ‘simulated’ between ‘The’ and ‘annual’

- Done.

General: There are many textual errors. Please have the whole text reviewed by a native English speaker before submitting the revised manuscript. Please do this for future submissions before the initial submission of the manuscript.

- Reply: Thank you so much for the careful review and correction! Besides, we have asked help from our native English speaker colleagues to correct the further textual errors in the whole manuscript.

References

Arendt, A. and 87 others: Randolph Glacier Inventory [5.0]: A Dataset of Global Glacier Outlines, Version 5.0, Global Land Ice Measurements from Space (GLIMS), Boulder, Colorado, USA., 2015.

Brun, F., Berthier, E., Wagnon, P., Kääb, A. and Treichler, D.: A spatially resolved estimate of High Mountain Asia glacier mass balances, 2000-2016, Nat. Geosci., (August), doi:10.1038/ngeo2999, 2017.

Dahri, Z. H., Ludwig, F., Moors, E., Ahmad, B., Khan, A. and Kabat, P.: An appraisal of precipitation distribution in the high-altitude catchments of the Indus basin, Sci. Total Environ., 548–549, 289–306, doi:10.1016/j.scitotenv.2016.01.001, 2016.

Gardelle, J., Berthier, E., Arnaud, Y. and Kääb, a.: Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011, Cryosph., 7(4), 1263–1286, doi:10.5194/tc-7-1263-2013, 2013.

Immerzeel, W. W., Wanders, N., Lutz, A. F., Shea, J. M. and Bierkens, M. F. P.: Reconciling high-altitude precipitation in the upper Indus basin with glacier mass balances and runoff, Hydrol. Earth

Syst. Sci., 19(11), 4673–4687, doi:10.5194/hess-19-4673-2015, 2015.

Lutz, A. F., Immerzeel, W. W., Gobiet, A., Pellicciotti, F. and Bierkens, M. F. P.: Comparison of climate change signals in CMIP3 and CMIP5 multi-model ensembles and implications for Central Asian glaciers, Hydrol. Earth Syst. Sci., 17(9), 3661–3677, doi:10.5194/hess-17- 3661-2013, 2013.

Palazzi, E., Hardenberg, J. Von and Provenzale, A.: Precipitation in the Hindu-Kush

Karakoram Himalaya : Observations and future scenarios, J. Geophys. Res. Atmos., 118, 85–100, doi:10.1029/2012JD018697, 2013.

Vincent, C., Wagnon, P., Shea, J. M., Immerzeel, W. W., Kraaijenbrink, P. D. A., Shrestha, D., Soruco, A., Arnaud, Y., Brun, F., Berthier, E. and Sherpa, S.: Reduced melt on debris- covered glaciers: investigations from Changri Nup Glacier, Nepal, Cryosph. Discuss., 1–28, 2016.

- Reply: Thanks a lot for the recommended citations. We have added most of them in the revised manuscript.

COMMENTS FROM EDITORS AND REVIEWERS

Interactive comment on **"Projection of future glacier and runoff change in Himalayan headwater Beas basin by using a coupled glacier and hydrological model"** *by* **Lu Li et al.**

Anonymous Referee #2

Received and published: 4 January 2018

The manuscript by Li et al. investigates the impact of climate change on glacier melt contribution to discharge in a medium-sized catchment in the Indus basin. To this end, a calibrated glacio-hydrological model was driven by statistically downscaled climate projections from one GCM under two GHG concentration scenarios. The simulations build on ensemble projections of glacier extent derived from a previous study by Lutz et al. (2016) who have already provided a more comprehensive assessment for the entire Indus basin. The manuscript mainly reports on model application in a particular basin and generally lacks novelty.

- Reply: Thanks for your comments. We have stated better the novelty of the study. Although there have been studies (i.e. Lutz et al. 2016; Li et al., 2016), looked at the hydrological projections in Indus river basin under climate change, but there is no common conclusion from the studies about the water future of western Himalayan region. Both studies suggest that more studies need to be done in the region.
  Furthermore, in Lutz et al. (2016), they used a corrected precipitation dataset (which is based on 0.25 degree gridded dataset APHRODITE) for historical period, because it was found that there is underestimation of precipitation at high-altitude area in Himalayan region (Immerzeel et al., 2015). In our study, we used a high-resolution (which is 3 km) dynamical regional climate model (WRF) precipitation data for correcting the underestimated precipitation (Li et al., 2017). Moreover, we have added two more ensembles of four GCMs according to the study of Lutz et al. (2016) for a more comprehensive comparison and uncertainty investigation for the future water cycle and availability in this Himalaya headwater Beas river basin. In the results, the uncertainty partition of hydrological projection from GCMs and statistical downscaling methods has been analyzed.

  We agree that the structure of our earlier version of the manuscript is not clear enough and made some confusion. We have sorted out the whole structure in the revised manuscript. The corrected precipitation based on Gauge and WRF has been moved to the first part of the method and results. We have also re-calibrated the model based on the new corrected precipitation. Furthermore, we have done the same correction for future precipitation. We have updated all the results based on the new simulations.

The glacio-hydrological modeling capitalizes on projections of future glacier extent from Lutz et al. (2016). Data derived from the Lutz et al. study should be moved to Materials and Methods and should be separated more clearly from the GSM-WASMOD modeling results obtained in the current study. This concerns section 4.3 including figures 10 and 11.

- Reply: Thanks for your comments. In our revised manuscript, we invited Arthur Lutz as co-author for re-running glacier evolution model by the same meteorological forcing from two new statistical downscaling methods under future scenarios of two ensembles of four GCMs (Rcp4.5 and Rcp8.5). All results were updated by the output from new simulations. We have also re-structured the manuscript including description of Data, methods and Results accordingly.

The manuscript has a poor structure and is more often than not hard to follow. For example, modeling results are presented and superficially discussed in "Results and discussion" which is however followed by a "Discussions" section that in fact introduces a completely new modeling experiment including data, methods, results and discussion. The additional material addresses the issue of uncertainty in precipitation data in high altitudes. This topic is without question relevant for hydrological modeling in the study region, however falls largely out of the scope of manuscript. In the remainder part (section 5.2) this topic is further discussed while a critical discussion of the main results presented in sections 4.2 - 4.4 is largely missing.

It is only mentioned by the end of the results section that only one GCM was down- scaled to drive the glacio-hydrological simulations while all previous sections give the impression that a GCM ensemble was used. A plethora of previous studies has shown that GCMs contribute a large share to total uncertainty in simulated hydrological impact and it is consequently common practice to drive (an ensemble of) impact models with a GCM ensemble. In this regard, the study clearly falls behind the state of the art and the material does not support significant conclusions.

The manuscript contains a large amount of figures and tables, 21 in total, of which some seem redundant and the authors should make an effort to streamline the mate- rial. For example, Table 4 listing all possible combinations of GCM, RCP and method of bias correction is largely identical in content to Table 2.

- Reply: Thanks for the comments. We agree and accept all of them. We feel sorry that we failed to present our work well in the original version. As we mentioned above, we agree that the structure of the previous manuscript was not clear enough and caused some confusion. We have now re-structured the whole manuscript. Furthermore, we have added two ensembles of four GCMs similar as in glacier projections (Lutz et al. 2016) for a more comprehensive comparison and uncertainty investigation for the future water cycle and availability in this Himalaya headwater Beas river basin.
  The rewritten manuscript follows those three main questions: "(1) How much uncertainty is in the precipitation over the ungauged high-altitude in Beas river basin? (2) How will the future water availability change due to higher glacier melt under warmer future in Beas river basin over the Himalaya region? (3) What are the uncertainties of the future water from GCMs or Statistical downscaling methods? To answer these questions, precipitations from a high-resolution WRF simulation and Gauge are investigated and a corrected precipitation is used for the hydrological simulation as the historical baseline.
  In the study, we use a glacio-hydrological model together with eight GCMs under two generation of scenarios, i.e. RCP 4.5 and RCP 8.5 and two statistical downscaling (SD) methods. We firstly focus on the simulation of the present day water cycle and validation of the simulated discharge by using the observed discharge. The uncertainties of the precipitation over high-altitude area and hydrological simulation are further discussed. Besides, the future climate change and glacier extent change and hydrological changes are investigated. At last, the uncertainty from GCMs and statistical downscaling methods is analyzed and discussed before presenting the main conclusions."
  In this revised manuscript, we have removed Fig 3, Fig.5 and Table 2. We also split section 5.1 and fill into three parts: 1) section 2.2 Data, 2) section 3.1 of precipitation correction and 3) section 4.1 corrected precipitation and section 4.2 GSM-WASMOD model calibration and validation.

The standard of English needs to be improved throughout the manuscript. While the meaning is usually (but not always) clear, there are a lot of grammatical errors (far too

many to list) and diction is often poor.

- Reply: Thanks for your comments. We have carefully checked the typos and grammatical errors through the whole revised manuscript and a native English speaker colleague has also corrected it.

Specific comments

L. 11: Why would the glacier melt lead to extreme rainfall?

- Reply: Thanks for the comment. That is obviously a mistake. We have corrected it: "The changes in glacier melt may lead to droughts as well as extreme floods in the Himalaya basins, which are vulnerable to the hydrological impacts."

L. 13: I strongly disagree with the use of the term RCM when referring to the two methods of GCM bias correction/downscaling applied in this study. The term RCM describes numerical prediction models.

- Reply: Thanks for the comment. We changed them all in the revised manuscript to be "statistical downscaling methods".

L. 30-32: Colloquial, please rephrase.

- Done.

L. 36: Please correct to "CMIP5"

- Corrected.

L. 67: Correct to "Mishra 2015"

- Corrected.

L. 88: Unclear, please rephrase.

- Done.

L. 115-117 : This section describes the study basin/region; information on the model and data used should be moved to the corresponding sections.

- Done.

L. 115: Please correct to "meteorological"

- Corrected.

L. 130: Was the GSM module developed in the scope of this study? If not, please add the reference to the original publication.

- Reply: Thanks for the comment. The GSM module is not original developed in this study. We have already added the original references in the revised manuscript.

L. 148: What was the reason for choosing a modeling resolution of 10 km? Most of the input data sets do seem to support a higher modeling resolution; please clarify.

- Reply: Thanks for the comments. We have now re-run all the simulations at 3*3 km resolution and found that the results of calibration and validation were not improved comparing with the results from 10*10 km resolution simulations. It was not a surprising because of limited gauge data that we have in the study area. According to the previous studies and analysis of the influence of interpolation and station density on gridded daily data (i.e. Dirksa et al. 1998; Hofstra et al., 2010; Xu et al., 2013), the results showed that the network density could introduce biases in the mean and variance of the grid values (i.e. precipitation and temperature) compared to those expected for the true area-averages.
  However, concerning the precision of routing, glacier revolution and smooth of discharge graph and 'step change' because of the coarse resolution, we finally decided to use the 3km simulation in the revised manuscript. All the Tables and figures are updated by new simulation results.

- Dirks, K.N., Hay, J.E., Stow, C.D. and Harris, D., 1998. High-resolution studies of rainfall on Norfolk

Island: Part II: Interpolation of rainfall data. *Journal of Hydrology*, *208*(3-4), pp.187-193.

- Hofstra, N., New, M. & McSweeney, C. Clim Dyn (2010) 35: 841. https://doi.org/10.1007/s00382-009-0698-1
- Xu, H., Xu, C.Y., Chen, H., Zhang, Z. and Li, L., 2013. Assessing the influence of rain gauge density and distribution on hydrological model performance in a humid region of China. *Journal of Hydrology*, *505*, pp.1-12.

L. 149: It was mentioned earlier that potential evaporation was only available from one station. Were these station values used for the entire basin? Please clarify.

- Reply: There is only one pan-evaporation station during 1996-2011 in the study region. It didn't show improvement in the simulation with observed Epan and it results in inconsistency to combine it. After a few testing run, we decided not to use it in the simulation. We have updated this in the Data section of the revised manuscript.

L. 155-156: Unclear, please rephrase.

- We have added more explanation here in the revised manuscript: "The routing method in GSM-WASMOD is called NFR routing algorithm (Gong et al. 2009, 2010), which was developed to adapt to the coarse resolution hydrological modeling. This is a scale-independent routing method for network-response function using high-resolution aggregated hydrographgy HYDRO1k. The algorithm preserves the spatially distributed time-delay information in the form of simple network-response functions for any low-resolution grid cell in a large-scale hydrological model."

Section 3.4: 1) The authors miss to describe and reference the 21st century GCM ensemble data used in the study. Please add a section or paragraph.

- Thanks for the comment. We have added two ensembles of four GCMs (Lutz et al. 2016) for comparison in the revised manuscript, and more clarification has been added in the Data section and in Table 2.

2) Lutz et al. (2016) applied the same GCM ensemble but a different downscaling approach to simulate the future glacier extent used in this study. Why did the authors choose a different downscaling technique? Given that the downscaling technique is found to have a profound effect on projected precipitation and temperature (which drive both the simulated glacier extent and melt), how does this inconsistency affect the results for the Beas river basin and the conclusions drawn?

- Reply: Thanks for the comment. We agree that the different SD methods may result in inconsistency in the simulations. After a careful consideration of the disadvantages of perfect prognosis (PP) methods and the advantages of bias correction methods, the downscaling methods of SDSM and SVM used in the original manuscript were replaced by two bias correction methods of DBC and LOCI in the revised manuscript.

  Both SDSM and SVM are regression-based downscaling methods, which involve estimating the statistical relationship (e.g. linear relationship for SDSM and nonlinear relationship for SVM) between large scale predictors (e.g. vorticity, mean sea-level pressure, geopotential height and relative humidity) and local or site-specific predictands (e.g. precipitation and temperature) using observed climate data. The reliability of a regression-based method relies on relationships between observed daily climate predictors and predictands. However, these relationships are usually weak, especially for daily precipitation. In addition, the regression-based method is usually incapable of downscaling precipitation occurrence and generating proper temporal structure of daily precipitation, which is critical for hydrological simulations. Moreover, the PP downscaling method establishes relationship between predictors and predictands for the historical period and then applies it to future periods. However, this relationship may not hold for the future in a changed climate. This may partly explain why there was a jump between downscaled historical and future precipitation and temperature simulation in our previous manuscript. In particular, the relationship between predictors and predictands established using reanalysis predictors are applied to GCM predictors based on an assumption that reanalysis predictors and GCM predictors are both "perfectly" simulated at the grid scale (Wilby et al., 2002; Dibike and Coulibaly, 2005; Chen et al., 2011a). While reanalysis and GCM data do share some similarities, they are completely independent. Reanalysis data aim at representing the real world, whereas GCMs operate in their own virtual world. This may further result in the jump of precipitation and temperature between historical and future period.

In our revised manuscript, the bias correction methods involve estimating a statistical relationship between a climate model variable (e.g. precipitation) and the same variable of the observations to correct the climate model outputs. The use of bias correction methods is usually considered as reasonable way to achieve physically plausible results for impact studies. Compared to PP methods, bias correction methods are relatively simple to use and negate the prerequisite of a strong relationship between local-scale variables and large scale climate model variables. Previous work indicates that statistical downscaling using GCM precipitation or temperature directly as a predictor performed much better than using other predictors.

We are now using two new bias correction methods (DBC and LOCI) and have added more comprehensive validation in the results section 4.3. All the relevant parts including introduction, methodology and results in the revised manuscript have been updated.

4) Sections 3.4.1 and 3.4.2 need to be rewritten to enhance comprehensibility. In the current version, it is impossible to understand how both downscaling approaches work.

- Thanks for the comment. We have rewritten this part and made it more understandable in the revised manuscript.

L. 209-215: "SSVM is directly used to construct the relationship between hydrological data and atmospheric variables" and "The calibration of downscaling models used the station-scale hydrological data and GCM historical atmospheric variables to construct the relationship": I understood from the earlier text that both techniques were used the downscale GCM simulated atmospheric variables to station-scale meteorological data which subsequently were used to drive the glacio-hydrological simulation. Did the authors establish a direct statistical relationship between atmospheric variables and hydrological fluxes? Please clarify.

- Reply: We have re-run all the simulations based on two new bias correction methods. The methodology and results have been updated in the revised manuscript accordingly. Please see the reply on the early comment of section 3.4, 2).

Section 3.5: 1) In L. 220, Li et al. 2013a or Li et al. 2013b?

- We have corrected the reference to be Li et al. 2013a.

2) Glacier mass balance data were apparently used for calibration, but this data-set has not been described or mentioned yet. Please add a description to the data section.

- We have added more information about the glacier mass balance data that we used in the section 2.2 of Data: "The annual glacier mass balance data of Chhota Shigri Glacier used in the model calibration are taken from the previous studies of Berthier et al. (2007), Vincent et al. (2013), Azam et al. (2016)." Besides, we have also added more explanation in the section 3.6: "There is an intra-regional variability of individual glacier mass balance in High Mountain Asia (HMA) and less negative mass balance than most other estimates according to the recent study of Brun et al. (2017). From the study, the annual glacier mass balance is -0.49+/-0.2 m w.e.yr-1 in Spiti-Lahaul region (where Chhota Shigri glacier locates) during 2000-2008 based on ASTER and 0.37+/-0.09 m w.e.yr-1 in Western Himalaya region from RGI Inventory during 2000-2016 based on ASTER. Besides, a detailed map of elevation changes during 2000-2011 in Spiti-Lahsul region based on SPOT5 DEM is given in the study of Gardelle et al. (2013), which showed that the changes of the glaciers in the Beas river basin is quite similar as the changes in Chhota Shigri glacier during 2000-2011 in general, although there is variability both in independent glacier and over the region. Furthermore, in our study basin, the glaciological mass balance series published in Spiti-Lahaul region (of HMA) that is available for comparison are the Chhota Shigri glacier and Bara Shigri glacier (Berithier et al. 2007). In which, the only one is long enough to be comparable to our simulation period is the Chhota Shigri glacier (2002-2014), which has also geodetic mass balance for validation (Azam et al. 2016). So we used the mass balance data of Chhota Shigri glacier as a representation for the glaciers in our small basin."

3) The efficiency criteria listed seem to refer to simulated discharge only. How was model efficiency evaluated with respect to glacier mass balance?

- We manually adjusted the parameters of glacier module according to the annual glacier mass balance data from previous studies. The bias is used for evaluation with respect to glacier mass balance. We have added the explanation in the revised manuscript. Please see section 3.6.

4) Were discharge and glacier mass balance calibrated simultaneously?

- We firstly 'pre-calibrate' all parameters according to the total discharge. Then we manually adjusted the parameters of glacier module according to the glacier mass balance. At last, we set the glacier module parameters and re-calibrate the other parameters according to discharge data one more time. We have added more clearly explanation in the revised manuscript.

L. 242 "worked fine": Colloquial, please rephrase. Further, I cannot see how Fig. 5 adds important new information. If its only purpose was to show that the model "worked fine", the figure can be removed.

- Thanks for the comment. We have removed Figure5.

L. 245: It was mentioned earlier that glacier mass balance data were used to calibrate GSM-WASMOD; are those the same data as used here for validation?

- Thanks for the comment. We used the mass balance data for calibration and also compared the glacier mass balance for validation in the section of 4.2 in the revised manuscript.

L. 250: Table 4 formally belongs to the methods section and should be referenced

there.

- Thanks for the comment. We have changed it.

L. 255-265: The two downscaling methods seem to introduce a large uncertainty with respect to future climate in the region. How does this uncertainty compare to the spread between the different GCMs?

- We have added two ensembles of four GCMs (Lutz et al., 2016) in the revised manuscript and compared the uncertainty from statistical downscaling methods and from GCMs in the revised manuscript. Please see section 5.2.

L. 294 “It shows that the summer peak of runoff sifts to the other seasons in Beas river basin”: Cannot be inferred from the figure.

- Thanks for the careful comment. We have modified it.

L. 300 and following: It is mentioned here for the first time that only GCM was down- scaled to drive the glacio-hydrological model. This should have been made clear in the methods section.

- Thanks for the comment. We have corrected it and updated the methodology and results in the revised manuscript.

Tab. 2: Please rephrase the caption and correct to “glacier evolution”; “Selected model” in the table heading is rather ambiguous and could be replaced by “GCMs”

- Done.

Table 3: Please correct to “validation”, “Nash-Sutcliffe coefficient” and “NS_d” (row 6); typographical error in the last row; missing space before table number.

- Done.

Table 5: Please provide a more informative caption. I assume ensemble median and range are show. “Change” should be spelled lower case. Does the table show changes over the glacierized area or for the entire river basin?

- We have added a new informative caption for Table 5. Yes, the values are mean with range of minimum and maximum values. This is the result from the whole river basin. We have clarified it in the revised manuscript.

Fig. 2: In the legend, please correct to “Simulated dis”

- Done.

Fig. 3: Please add the observed discharge for reference

- Done.

Fig. 4: Please correct to “Monthly hydrographs”. The quality of the Figure should be improved.

- Done.

Fig. 6: The observed data shown seem to be mean values over certain time periods rather than estimates for a single year (e.g. 1999–2004 in Vincent et al. 2013), but are depicted as points in the figure which is misleading. Please correct. Further, please add a table listing all external glacier MB data including reference period and estimation method.

- Thank you for the comment. We have corrected the data and its reference in the Fig. 6. We have also added Table 4 for listing all of the observed annual mass balance data from previous studies, which was used in the glacier module calibration and validation in the revised manuscript.

Fig. 7+8+9: I strongly disagree with the use of the term “RCM” when the authors actually refer to bias correction methods, please correct. Please revise the captions. Do the figures show the ensemble mean? If yes, please add the ensemble range.

- We have corrected the use of term “RCM” in the whole revised manuscript. Besides, we have added the ensemble mean and range in Fig 7, Fig 8, Fig 15 and Fig 16.

Fig. 10: Y-axis label should read “Glacier”

- Corrected.

Fig. 11: Is this the ensemble mean?

- Yes, it is the ensemble mean. We have removed this figure in the revised manuscript regarding in order to reduce the number of figures that we have in the paper.

Fig. 12: The figure needs profound revision. 1) I can only guess that the numbers in the legend refer to the index given in Table 4. Listing all ensemble members in the legend is somewhat obsolete since they are not distinguishable in the plot. 2) The caption claims that results for only one GCM are shown (CANESM2) while the figure apparently shows the whole ensemble. 3) Are both RCPs shown? If yes, please color- code accordingly. 4) In all simulations glacier melt discharge approaches 0 by the end of the century while according to Table 5 glacier cover remains larger than 0. Please explain. 4) Why is glacier-melt discharge given in negative numbers?

- Thanks for the comment. We have re-plot the figure into two new figures of Fig. 13 and Fig.14 for a clearer clarification in the revised manuscript. In the new figures, the different bias correction methods are represented by different colors (blue for LOCI and red for DBC), while the different GCMs are shown in different line styles with (for RCP45) or without (for RCP85) marker.
  We have corrected the glacier-melt discharge to be positive values. And the glacier discharge in Fig 14 is the total discharge including rainfall discharge, snowmelt discharge and ice-melt discharge from glacier-covered grids. We have clarified clearer in the revised manuscript. The result in Fig 14 is now consistent with the results in Fig. 12 of glacier extent evolution in Beas river basin.

Fig. 14: The two subfigures seem to show exactly the same data with respect to the single ensemble members. Please double-check.

- Thank you so much for the careful review and corrections! We have corrected them according to the above comments about the Tables and Figures in the revised manuscript. Besides, all the figures and tables have been updated by the new results in the revised manuscript with respect to the added new GCMs and statistical downscaling methods.

Interactive comment on **"Projection of future glacier and runoff change in Himalayan headwater Beas basin by using a coupled glacier and hydrological model"** *by* **Lu Li et al.**

A. Sharma

abhishek09406.nith@gmail.com

Received and published: 14 November 2017

Dear authors,

This is a very useful study that has been conducted for the data-scarce Himalayan Basin. I have gone meticulously through the paper and I have the following queries:

1) Line 24. The study helps to understand the hydrological impacts of climate change in North India and make a contribution to stakeholders and policymakers with re- spect to the future of water resources in North India. -However, since only one GCM (BCC_CSM 1.1) is used for the study, how accurate would be the predictions to be able to be referred by the policymakers? -How is the use of this particular GCM, 'Bei- jing Climate Center Climate System Model' (BCC_CSM 1.1), justified for use over the Himalayan basin? Please elaborate on this issue.

- Thanks for your positive evaluation in general and for your professional comment. We agree with it and we have added two ensembles of four GCMs (lutz et al. 2016) and invited Arthur Lutz as co-author for re-run glacier extent projections by the same meterological forcing as hydrological model in the revised manuscript for a more comprehensive comparison and uncertainty investigation for the future water cycle and availability in this Himalaya headwater Beas river basin.

2) Line 237. Authors should present a figure showing the location of Chhota Shigri glacier in the Beas Basin. Because according to SERB report (Ramanathan, 2011), Chhota Shigri glacier is a part of the Chandra Basin. Chandra basin is a sub-basin of the Chenab river basin according to IndiaWRIS basin maps and the SERB report by Ramanathan (2011).

- Thanks for the comment and reference. We have corrected it in the manuscript: "The Beas river basin is located in Spiti-Lahaul region, where the available glaciological mass balance series published for comparison are the Chhota Shigri glacier and Bara Shigri glacier (Berithier et al. 2007). The Chhota Shigri glacier is the only one which has been well studied and has detailed and longer period of glacier mass balance data, which also has geodetic mass balance data for validation (Azam et al. 2016). The Chhota Shigri Glacier is a part of the Chandra Basin, which is a sub-basin of the Chenab river basin (Ramanathan, 2011), but it is attached to northeast boundary of Beas river basin, which is close to Manali and Bhunter stations (Fig 1.). In this case, it is used for glacier module calibration in the study, which is to be comparable to the simulation."

  We have also added the location of Chhota Shigri glacier in the Fig. 1 of the revised manuscript. Please see the Fig 1 in the "reply to the RC1".

3) Line 150. Chhota Shigri glacier Area is about 16 Km2 (Ramanathan, 2011), the resolution of the hydrological model GSM-WASMOD is 10*10 Km2.The limitation mea- sured on line 306 also mentions the same thing. However, I feel that the model in the study is too coarse to be able to accurately represent the outflow from the glacier melt. How is such a coarse model justified to be used for representing glacier melt from such small area glaciers and the glacier evolution?

- Reply: Thanks for the comment. We understand the concern from you. We used mass balance data of Chhota Shigri glacier for comparison with the simulation of the study, because it is the well monitored and studied glacier whose data are available for using. From the revised new Figure 1, we can see that the Chhota Shigri glacier is very small glacier compared with the whole glacier cover in the Beas river basin. In the study, we are looking at the whole glacier extent of Beas river basin and its impact to the total basin runoff, instead of a single Chhota Shigri glacier, which has been done by several previous papers (i.e. Berithier et al. 2007, Azam et al.2016).

Furthermore, we have now re-run the model on 3*3 km resolution and updated all the results based on the new simulations.

4) Line115. Since the outlet station is Thalout station used for calibration of discharge, I would like to know what is the area of the Beas basin upto Thalout?

- Thanks for the comment and reference. We added the mark of watershed area up to Thalout in the new Fig 1. (please see Fig. 1 in the “reply to the RC1”).

Reference: Ramanathan, AL. (2011). Status Report on Chhota Shigri Glacier (Hi- machal Pradesh), Department of Science and Technology, Ministry of Science and Technology, New Delhi. Himalayan Glaciology Technical Report No.1,pp-88p.

Twenty-first-century glacio-hydrological changes in the Himalayan headwater Beas river basin

Lu Li[1*], Mingxi Shen[3], Yukun Hou[3], Chong-Yu Xu[2,3], Arthur F. Lutz[5], Jie Chen[3], Sharad K Jain[4], Jingjing Li[3], Hua Chen[3]

[1]NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Jahnebakken 5, 5007 Bergen

[2]Department of Geosciences, University of Oslo, Norway

[3]State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, China

[4]National Institute of Hydrology, Roorkee, India

[5]FutureWater, Costerweg 1V, 6702 AA, Wageningen, Netherlands

**Correspondence to:* Lu Li (luli@norceresearch.no)

Abstract. The Himalayan Mountains are the source region of one of the world's largest supplies of freshwater. The changes in glacier melt may lead to droughts as well as floods in the Himalaya basins, which are vulnerable to hydrological impacts. This study used an integrated glacio-hydrological model: Glacier and Snow Melt - WASMOD model (GSM-WASMOD) for hydrological projections under 21st century climate change by two bias correction methods under two Representative Concentration Pathways (RCP4.5 and RCP 8.5) in order to assess the future water (i.e., water availability and hydrological regime) change at the Himalayan Beas basin. Besides, the glacier extent loss of the 21st Century from eight GCMs was also investigated as part of the glacio-hydrological modelling as an ensemble simulation.

A high-resolution WRF precipitation suggested much heavier winter precipitation over high altitude ungauged area in the Himalaya Beas river basin, which was used for precipitation correction in the study for both the historical period and future scenarios. The glacio-hydrological modeling shows that at present, the glacier ablation accounts for about 5% of the annual total runoff during 1986-2004 in this area. Under climate change, the temperature will increase by 1.8 °C (RCP4.5) and 2.8 °C (RCP8.5) for the early future (2046-2065), and by 2.3 °C (RCP4.5) and 5.4 °C (RCP8.5) for the late future (2080-2099). In general, the uncertainty of projection from RCP8.5 is much larger than that from RCP4.5. Comparing two bias correction methods, i.e., the daily bias correction (DBC) and the local intensity scaling (LOCI), there is a wider spread of precipitation and temperature increase from DBC than that from LOCI. It is very likely that the Beas river basin will get warmer and wetter compared to the historical period. In this study, the glacier extent in the Beas river basin is projected to decrease over the range of 63 - 81 % (RCP4.5) and 76 - 87 % (RCP8.5) by the middle of the century (2050) and 89-99 % (RCP4.5) and 93-100 % (RCP8.5) at the end of the century (2100) compared to the glacier extent in 2005. This loss in glacier area will, in general, result in a reduction in glacier discharge in the future, while the future runoff is most likely to have a slight increase because of the increase from both precipitation and temperature under all the scenarios. However, there is widespread uncertainty regarding the changes of total discharge in the future, including the seasonality and magnitude. In general, the largest increase of river total discharge also has the largest spread. The uncertainty of future hydrological change is not only from GCMs but also comes from the bias correction methods. A decrease of discharge is found in July from DBC, while it is opposite from LOCI. Besides, there is a drop in evaporation in September from DBC, which cannot be seen from LOCI. The study helps to understand the hydrological impacts of climate change in North India and contributes to stakeholders and policymakers' engagement in the management of future water resources in North India.

1 INTRODUCTION

Outside the polar regions, the Himalayas store more snow and ice than any other place in the world. Hence, Himalayas are also called the ‘Third Pole” and are one of the world’s largest suppliers of freshwater. Similar to the glaciers all over the world, the Himalayan glaciers are also changing as a result of global warming. Changes in glacier mass, ice thickness, and melt will impart major changes in flow regime of Himalayan basins. Among other things, it may lead to increased prevalence of droughts and floods in the basins of Himalayan rivers. Hydrological models have been developed and are being used as the main assessment tool to estimate the impacts of climate change for future water resources. However, most hydrological models either do not have a representation of glaciers (Ali et al., 2015; Horton et al., 2006; Stahl et al., 2008) or do not have proper glacier representation with limited glacier cover assumption (i.e., assumptions with intact glacier cover, 50% or none glacier cover) (Akhtar et al., 2008; Hasson 2016; Aggarwal et al. 2016). A glacio-hydrolgical model which includes a comprehensive parameterization of glaciers is highly required for the water resources assessment of high mountainous basins over the Himalayan region. Recently, Lutz et al. (2016) investigated the future hydrology by a glacio-hydrological model with a proper representative glacier module over the whole mountainous Upper Indus Basin (UIB) with an ensemble of statistically downscaled CMIP5 GCMs. Results obtained by them indicated a shift from summer peak flow towards the other seasons for the most ensemble members. An increase in intense and frequent extreme discharges is likely to occur for the UIB in the future of the 21st century according to their study. Besides, Li et al. (2016) applied a hydro-glacial model in two basins in the Himalayan region and assessed the future water resources under climate change scenarios, which were generated by two bias corrected COordinated Regional climate Downscaling EXperiment (CORDEX, Jacob et al. 2014) data from the World Climate Research Program (WCRP). However, their results showed a conflicting future glacier cover at the end of the century under different scenarios. Especially in Beas river basin, the result indicated that the glaciers are predicted to gain mass under Representative Concentration Pathways (RCP) 2.6 and RCP 4.5 while losing mass under RCP 8.5 for the late future after 2060. This conflicting future is not only seen for the glacier projections but also for the river flow. The impact of glacier melt on river flow is noteworthy in the future in the Himalaya region. On the one hand, some studies suggested an increase of future water availability in Upper Indus Basin over Himalayan region for the 21st century (Ali et al., 2015; Lutz et al., 2014; Khan et al., 2015). On the other hand, a substantial drop in the glacier melt and subsequent reduction in water availability are suggested for the near future by the other studies (e.g., Hasson, 2016). Furthermore, a few recent studies suggested highly uncertain water availability in the late/long-term future and no consistent conclusion can be seen in the UIB over Himalaya region (e.g., Lutz et al., 2016; Li et al., 2016; Hasson et al., 2016). As of now, there is a lack of in-depth understanding of the water resources in the future, which will be highly affected by glacier melting in the mountainous basin over Himalayan region (Hasson et al., 2014; Li et al., 2016; Lutz et al., 2016; Ali et al., 2015).

To investigate the climate change impact on the future water availability, the variables produced by GCMs are downscaled by an appropriate regional climate model (RCM) for use as inputs to hydrological models. This approach is adopted because the outputs of GCMs are too coarse to directly drive hydrological models at regional or basin scale (Akhtar et al., 2008). However, the RCM simulations have systematic biases resulting from an imperfect representation of physical processes, numerical approximations and other assumptions (Eden et al., 2014; Fujihara et al., 2008; Anand et al. 2017). Furthermore, some recent studies have evaluated CORDEX data and have highlighted the need for proper evaluation before use of RCMs for impact assessment for sustainable climate change adaptation. For instance, Mishra (2015) analyzed the uncertainty of CORDEX, and the results showed that the RCMs exhibit large uncertainties in temperature and precipitation in South Asia regional model and are unable to reproduce observed warming trends. Singh et al. (2017) compared CORDEX with GCMs and found that no consistent added value is observed in the RCM simulations of changes in Indian summer monsoon rainfall over the recent periods in general. In this case, concerning the large bias from GCMs and RCMs, the statistical downscaling is still the most popular and widely used approach for providing input in hydrological models in quantifying the impact of climate change on hydrology (e.g., Fang et al., 2015; Fiseha et al., 2015; Smitha et al., 2018). Previous studies have applied statistical downscaling methods based on GCM or RCM, as input for hydrological models over different basins in the world, including two widely used methods, i.e., regression-based downscaling methods (Chen et al., 2010, 2012) and bias correction methods (Troin et al., 2015; Johnson and Sharma, 2015; Li et al., 2016; Ali et al., 2014; Teutschbein and Seibert, 2012). The regression-based downscaling methods, e.g., Statistical Downscaling Model (SDSM) (Wilby et al. 2002; Chu et al. 2010; Tatsumi et al. 2014) and support vector machine (SVM) (Chen et al. 2013), which involve estimating the statistical relationship (e.g., linear relationship for SDSM and nonlinear relationship for SVM) between large scale predictors (e.g., vorticity, mean sea-level pressure, geopotential height and relative humidity) and local or site-specific predictands (e.g., precipitation and temperature) using observed climate data. The reliability of a regression-based method relies on relationships between observed daily climate predictors and predictands. However, these relationships are usually weak, especially for daily precipitation (Chen et al. 2011). Besides, the regression-based method is usually incapable of downscaling precipitation occurrence and generating proper temporal structure of daily precipitation, which is critical for hydrological simulations. Moreover, this perfect prognosis (PP) downscaling method establishes a relationship between predictors and predictands for the historical period and then applies it to future periods. However, this relationship may not hold for the future in a changing climate. In particular, the relationship between predictors and predictands established using reanalysis predictors are applied to GCM predictors based on the assumption that reanalysis predictors and GCM predictors are both "perfectly" simulated at the grid scale (Wilby et al., 2002; Dibike and Coulibaly, 2005; Chen et al., 2011).

Another widely used statistical downscaling method, i.e., bias correction method, which involves estimating a statistical relationship between a climate model variable (e.g., precipitation) and the same variable of the observations to correct the climate model outputs. The use of bias correction methods is usually considered as reasonable way to achieve physically plausible results for impact studies. Some articles found that bias correction results in physical inconsistencies since the corrected variables are not independent of each other (e.g., Immerzeel et al., 2013; Cannon et al., 2015). For instance, although bias corrected RCM precipitation data are expected to improve the hydrological calibration results, they will no longer be consistent with modeled other variables, e.g., temperature, radiation. However, compared to PP methods, bias correction methods are relatively simple to use and negate the prerequisite of a strong relationship between local-scale variables and large-scale climate model variables. In this case, we chose bias correction method for downscaling in the study over Himalayan Beas river basin with very complex topography.

There are wide uncertainty resources in hydrological impacts under climate change and a number of articles have studied them (i.e., Chen et al., 2011, 2013; Pechlivanidis et al., 2017; Samaniego et al., 2017; Vetter et al., 2017; Shen et al., 2018). Chen et al. (2011) investigated the uncertainty of six dynamical and statistical downscaling methods in quantifying the hydrological impacts under climate change in a Canadian river basin. A significant uncertainty was found to be associated with the choice of downscaling methods, which is comparable to uncertainty from GCM. Chen et al. (2013) stated that the importance of uncertainty is geography dependent. The uncertainty of future extreme events is typically larger compared to that of the mean discharges. They noted that climate models usually underestimate the inter-annual variance of precipitation compared to the observations. Further, uncertainty associated with the choice of empirical downscale methods is similar to that related to RCM simulations. The study by Chen et al. (2013) also emphasized the importance of using several climate projections to delineate uncertainty when attempting a climate change impact study over a new region. Furthermore, a project called “Inter-Sectoral Impact Model Intercomparison Project phase 2” (ISI-MIP2) provides a excellent opportunity to investigate the propagation of forcing and model uncertainties impact on the century-long timer series of hydrological variables using an ensemble of hydrological model projections across a broad range of climate scenarios and regions in the world (Pechlivanidis et al., 2017; Samaniego et al., 2017). For example, in the study of Samaniego et al. (2017), six hydrological models were set up in seven large river basins over the world, which were forced by bias-corrected outputs from five GCMs under RCP2.6 and RCP8.5 for the period 1971-2099. They found that GCM uncertainty mostly dominated over Hydrological model uncertainty for the projections of runoff drought characteristics in general and emphasized the need for multi-model ensembles for the assessment of future drought projections. Pechlivanidis et al. (2017) investigate the future hydrological projections based on five regional-scale hydrological models driven by five GCMs and four RCPs for five large basins over the world. They found that the high flows are sensitive to changes in precipitation, while the sensitivity varies between the basins. The results from their study also indicated that climate change impact studies can be highly influenced by uncertainty both in the climate and impact models; however, in the dry regions, the sensitivity to climate modelling uncertainty becoming greater than hydrological model uncertainty. More evaluation of uncertainty sources in projected hydrological changes under climate change was made by Vetter et al. (2017) over 12 large-scale river basins. The results showed that in general, the most significant uncertainty is related to GCMs, followed by RCPs and hydrological models, which are the lowest contributors of uncertainty for Q_{10} and mean flow, but the hydrological models contribute more significant for Q_{90}.

However, the previous climate change impact studies have presented conflicting results regarding the largest source of uncertainty in essential hydrological variables, especially the evolution of streamflow and derived characteristics over glacier feed river basin over high mountainous ungauged or poor-gauged area, e.g., Himalayan region (Hasson et al., 2014; Li et al., 2016; Lutz et al., 2016; Ali et al., 2015). At present, a complete understanding of the hydroclimate variability is also a challenge in the Himalayan basins due to poor in-situ coverage (Maussion et al., 2011) and incomplete or unreliable records (Hewitt 2005; Bolch et al. 2012; Hartmann and Andresky 2013). An overview of the variation in precipitation estimates of gridded products was provided by Palazzi et al. (2013), in which six gridded products are compared with simulation results from a global climate model EC-Earth despite having different resolutions. In the Himalayan region, precipitation is strongly influenced by terrain. The regional patterns and amounts of the precipitation are not always captured by global gridded precipitation datasets, e.g., Tropical Rainfall Measuring Mission (TRMM) (Huffman et al. 2007), ERA-Interim (ECWMF, Dee et al., 2011), Climate Research Unit (CRU) (Mitchell and Jones, 2005), and the Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) (Yatagai et al. 2012) (see also Biskop et al. 2012; Dimri et al. 2013; Ménégoz et al. 2013; Ji and Kang 2013). Previous studies showed that the high-resolution (<4km grid spacing) RCMs had demonstrated reasonable skill in reproducing precipitation distribution and intensity patterns over complex terrain (e.g., Rasmussen et al. 2011, 2014; Collier et al. 2013). A high-resolution Weather Research and Forecasting (WRF) dynamical simulation has been applied in the Beas basin in Himalaya showing promising potential in addressing the issue of high spatial variability in the complex terrain and high elevation precipitation (Li et al., 2017). This high-resolution WRF simulation from Li et al. (2017) provides an estimation of liquid and solid precipitation in high altitude areas, where satellite and rain gauge networks are not reliable.

The following questions are studied in this paper: (1) How much uncertainty is in the precipitation over the ungauged high-altitude in Beas river basin? (2) How will the future water availability change due to higher glacier melt under warmer future in Beas river basin over the Himalayan region? (3) How are the uncertainties of the future water from GCMs or statistical downscaling methods?

To answer these questions, precipitations from a high-resolution WRF simulation and Gauge are investigated, and corrected precipitation is used for the hydrological simulation for the historical baseline, as well as in the future scenarios. In the study, we use a glacio-hydrological model together with two ensembles of four GCMs under two generation of scenarios, i.e., RCP 4.5 and RCP 8.5, and two bias correction methods. We firstly focus on the simulation of the present day water cycle, calibration and validation of the glacier mass balance and discharge by observations. The uncertainties of the precipitation over the high-altitude area and hydrological simulation are further discussed. Besides, the future climate change, glacier extent change and hydrological change are investigated. At last, the uncertainty from GCMs and statistical downscaling methods is analyzed and discussed before presenting the main conclusions.

2 STUDY AREA AND DATA

2.1 Study area

The study area is Beas river basin upstream of the Pandoh Dam with a drainage area of 5406 km^2, out of which only 780 km^2 (14%) is under permanent snow and ice. It is one of the important rivers of the Indus River system. The length of the Beas River up to Pandoh is 116 km; among its tributaries, Parbati and Sainj Khad Rivers are glaciers fed. The altitude of the study area varies from about 600 m to above 5400 m above mean sea level (a.m.s.l.). The study area falls in a lower Himalayan zone and varies in climate due to elevation difference. The mean annual precipitation is 1217 mm, of which 70% occurs in the monsoon season from July to September. The mean annual runoff is 200 m^3/s, of which 55% occurs in the monsoon season and only 7.2% occurs in winter from January to March (Kumar et al., 2007). The mean temperature rises above 20ºC in summer and falls below 2ºC in January. The topography and drainage map of the river system along with rain gauge stations is shown in Fig. 1.

2.2 Data

The basin boundary in the study is delineated based on HYDRO1k (USGS, 1996a), which is derived from the GTOPO30 30-arc-second global-elevation dataset (USGS, 1996b) and has a spatial resolution of 1 km. HYDRO1k is hydrographically corrected such that local depressions are removed, and basin boundaries are consistent with topographic maps. Daily precipitation of 7 gauge stations, daily minimum and maximum temperature and relative humidity of 4 meteorological stations obtained from Bhakra Beas Management Board (BBMB) in India were used for GSM-WASMOD modelling. The discharge of Thalout station was used for GSM-WASMOD model calibration and validation, which was also obtained from the BBMB. The hydrological and meteorological data from 1990 to 2005 were used, which have undergone quality control in the previous studies (Kumar et al., 2007, Li et al., 2013a, 2015a). Glacier outlines were taken from the recently published Randolph Glacier Inventory (RGI 6.0) (2017) (https://doi.org/10.7265/N5-RGI-60). The annual glacier mass balance data of Chhota Shigri Glacier that are used in the model calibration are taken from the previous studies of Berthier et al. (2007), Wagnon et al. (2007); Vincent et al. (2013) and Azam et al. (2014). Two ensembles of four GCM models under RCP4.5 and RCP 8.5, including CamESM2, CSIRO_Mk3_6_0, Inmcm4, IPSL_CM5A_LR, MIROC5, MRI_CGCM3 and MRI-ESM1 (Taylor et al., 2012) are chosen for driving the empirical statistical downscaling future simulations (see in Table 2). Furthermore, the daily precipitation from a horizontal high-resolution of 3 km WRF simulation by Li et al. (2017) is also used in the study for further bias correction of high mountainous winter precipitation in all the simulations.

3 METHODOLOGY

3.1 Glacier- and snow- melt module (GSM)

A conceptual glacier- and snow-melt module (GSM) (Li et al., 2013a; Engelhardt et al., 2012) was used to compute glacier mass balances and melt-water runoff from the glacier in the study basin, which was only applied to the grid cells of the glacier-covered area. Those glacier grid cells were defined by ESRI ArcGIS system v. 9.0 (or higher) and set up before modeling based on the glacier outlines from the RGI (6.0) (2017) (Berthier, 2006; Raup et al., 2007). The gridded temperature and precipitation are interpolated based on the station data by Inverse Distance Weighted (IDW) method, in which the vertical temperature lapse rate of -6 °C km^{-1} is used to convert station temperature to the elevations of the grid cells (Kattel et al., 2013). The daily gridded temperature and precipitation were input data for the GSM module, which calculated both snow accumulation and melt-water runoff. A temperature-index approach (Hock, 2003; Engelhardt et al., 2012, 2017) was used in the study for the calculation of the conceptual GSM module. In the GSM module simulation, the precipitation shifted from rain to snow linearly within a temperature interval of ΔT (Table 1). Additionally, the liquid water from rain or melt infiltrated and refrozen in the snowpack, which filled the available storage. Runoff occurred when the storage was filled, which depended on the snow depth.

The snow melting started firstly, followed by the melting of the refrozen water and firn. At last, the ice started to melt when the firn has all melted away. We used different degree-day factors of firn (DDF_f) and ice (DDF_i), which are 15 % and 30 % larger than that of snow (DDF_s), respectively (Singh et al., 2000; Hock, 2003). The debris cover is not yet considered in the modeling right now. The related equations can be found in Table 1.

3.2 GSM-WASMOD model

A integrated glacio-hydrological model: Glacier and Snow Melt - WASMOD model (GSM-WASMOD) was developed by coupling the water and snow balance modeling system (WASMOD-D) (Xu, 2002; Widen-Nilsson et al., 2009; Gong et al., 2009; Li et al., 2013b, 2015b) with the GSM module. The spatial resolution of the GSM-WASMOD modeling is 3 km in the study. The daily precipitation, temperature and relative humidity from the observed stations were interpolated by the IDW method to 3 km resolution gridded data, which were used as input for the GSM-WASMOD model. For the temperature, the vertical temperature lapse rate of $-6\ ^{\circ}\mathrm{C\ km}^{-1}$ is used in the interpolation. GSM-WASMOD calculates snow accumulation, snowmelt, actual evapotranspiration (ET), soil moisture, fast flow and slow flow at the non-glacier area. The routing process of GSM-WASMOD model in the study is the aggregated network-response-function (NRF) routing algorithm, which was developed by Gong et al. (2009). The spatially distributed time-delay was calculated and preserved by the NRF method based on the 1 km HYDRO1k flow network, which is from the U.S. Geological Survey (USGS). The runoff generated in the resolution of 3 km grid was transferred by the NRF method based on the simple cell-response function. More details can be found in Gong et al. (2009). The equations of GSM-WASMOD model are shown in Table 1.

3.3 Glacier evolution parameterization

GSM-WASMOD is a conceptual glacio-hydrological model, which means that the glacier extent is not changing in the historical simulation. This assumption cannot be applied in future simulations under climate change since the future of the glacier extent is a crucial factor for the future hydrology in the Beas river basin. In this case, we used a basin-scale regionalized glacier mass balance model with parameterization of glacier area changes and subsequent aggregation of regional glacier characteristics (Lutz et al., 2013), to estimate future changes in glacier extent. It estimates changes in the glacier extent as a function of the glacier size distribution and distribution over altitude and temperature and precipitation. The model is calibrated to the observed glacier mass balance (e.g., Azam et al., 2014), and subsequently forced with an ensemble of statistically downscaled climate scenarios (section 3.4, Table 2). The model runs at a monthly time step to ensure that seasonal differences in the climate change signal are taken into account. A detailed description the glacier evolution parameterization is described in Lutz et al., (2013).

3.4 Bias correction methods

Since GCM outputs are spatially too coarse and too biased to be used as direct inputs to glacio-hydrological model for impact studies, downscaling or bias correction techniques must be applied for generating site-specific climate change scenarios (Rudd and Kay 2016). In this study, two bias correction methods, i.e., Daily bias correction (DBC) (Schmidli et al., 2006; Mpelasoka and Chiew, 2009; Chen et al. 2013) and Local intensity scaling (LOCI) (Schmidli et al., 2006; Chen et al., 2011), with different levels of complexity were applied for correcting GCM-simulated daily precipitation, temperature and relative humidity in the Himalayan Beas river basin under climate change of the 21st Century (i.e., 2046-2065 and 2080-2099).

3.4.1 Local intensity scaling (LOCI)

LOCI is a mean-based bias correction method, which corrects the precipitation frequency and quantity at monthly basis with the following three steps: (1) a wet-day threshold is determined from the GCM-simulated daily precipitation series for each calendar month to ensure that the threshold exceedance for the reference period equals the observed precipitation frequency in that month; (2) a scaling factor is calculated to ensure that the mean of GCM precipitation for the reference period is equal to that of the observed precipitation for each month; (3) the monthly thresholds and scaling factors determined in the reference period are further used to correct GCM precipitation in the future period. Since there is no occurrence problem for humidity, LOCI only corrects the mean value of GCM-simulated humidity for each month. In addition, the mean and variance of temperature are corrected using the variance scaling approach of Chen et al. (2011).

3.4.2 Daily bias correction (DBC)

DBC is a distribution-based bias correction method. Instead of correcting the mean value, the DBC method corrects the distribution shape of GCM-simulated climate variable. Specifically, the ratio (for precipitation and humidity) or difference (for temperature) between observed and GCM-simulated data in 100 percentiles (from 1th percentile to 100th percentile) at the reference period multiplied or added to the future time series for each percentile. The wet-day frequency of precipitation occurrence is corrected using the same procedure of LOCI. The DBC method is also carried out on a monthly basis.

Both bias correction methods are calibrated in the historical period of 1986-2005 from the observations. The calibration of downscaling models used the station-scale meteorological data and GCM historical variables to construct the relationship. The calibrated bias correction models are then utilized to predict the future climate change for the meteorological variables including precipitation, temperature and relative humidity in two periods, i.e., early future of 2046-2065 and the late future of 2080-2099, under both the RCP4.5 and RCP8.5 scenarios.

3.5 Precipitation correction

According to the previous studies over Himalaya and surrounding area (Winiger et al., 2005; Immerzeel et al., 2015; Ji et al., 2015; Shrestha et al., 2012), specifically in Beas river basin up to Pandoh, there are quite large uncertainties in precipitation over high altitude area. Li et al. (2017) applied the Weather Research and Forecasting model (WRF) over Beas river basin at high-resolution of 3 km in 1996-2005. The seasonal WRF precipitation compared with gauge rainfall data is shown in Fig. 2, which indicates that the WRF model predicts more winter precipitation at high altitude area in Beas river basin. Currently, we have no rainfall and snowfall observation data at the high mountainous area. The highest gauge station is Manali (see Fig. 1), whose altitude is 1926 m a.m.s.l.

In this study, we have compared the data from the high-resolution 3 km WRF simulation with gauge precipitation during the overlapping period of 1996-2005. The winter precipitations from gauge and WRF over different altitudes are listed in Table 3, from which we can see that the winter precipitations from WRF at mountainous over 4000 m and 4800 m a.m.s.l. are almost triple times as that from Gauge. This is comparable with the results from previous studies (Immerzeel et al., 2015; Dahri et al., 2016). For example, Immerzeel et al. (2015) estimated annual precipitation of altitude over upper Indus Basin and found that an increase of over 300% over the uncorrected high mountainous precipitation between 3751 m and 4250 m a.m.s.l. It was also suggested in their study that APHRODITE underestimates annual precipitation by as much as 200% over the upper Indus Basin (Immerzeel et al., 2015). In the study of Dahri et al. (2016), a basin-wide, seasonal and annual correction factor for each gridded precipitation product was provided based on a geo-statistical analysis of precipitation observations which revealed substantially higher precipitation in most of the sub-basins compared to earlier studies. For the high-altitude western and northern Himalayan basins, including Indus, the correction factor for winter precipitation varies from 1.93 to 2.47 and from 1.82 to 4.44 comparing with APHRODITE and TRMM, respectively. Considering that we lacked observed precipitation over the high mountainous area in Beas river basin, especially in the winter period, we bias corrected the winter precipitation (December - March) from gauge station with the WRF precipitation to provide more reliable precipitation for the Glacier-hydrological model calibration and validation. However, we cannot evaluate the correction factors of WRF/Gauge for winter precipitation, although WRF shows reasonable performances on winter precipitation over complex terrain in previous studies (Rasmussen et al., 2011; Li et al., 2017). In this case, we chose an average value of 2.7 in the study for the winter precipitation (DJFM) correction in Beas river basin for all the grids whose altitude is over 4800 m a.m.s.l.. The same bias correction is also applied for the winter precipitation for all the future scenarios.

3.6 GSM-WASMOD Model calibration

There are six parameters to be calibrated in GSM-WASMOD by searching for an optimal parameter set for the discharge at the Thalout station, including the snowfall temperature a_1, snowmelt temperature a_2, actual evapotranspiration parameter a_4, the fast-runoff parameter c_1, the slow-runoff parameter c_2 and the degree-day factor of snow DDF_s. The observed average annual glacier mass balance and discharge in Beas River basin are both used for the calibration in the study. There is an intra-regional variability of individual glacier mass balance in High Mountain Asia (HMA) in the recent study of Brun et al. (2017). From their study, the glacier mass balance is -0.49+/-0.2 annual meter water equivalent (m w.e. a^{-1}) in Spiti-Lahaul region (where Chhota Shigri glacier locates) during 2000-2008 based on ASTER and 0.37+/-0.09 m w.e. a^{-1} in Western Himalaya region from RGI Inventory during 2000-2016 based on ASTER. Besides, a detailed map of elevation changes during 2000-2011 in Spiti-Lahaul region based on SPOT5 DEM is given in the study of Gardelle et al. (2013), which showed that the changes of the glaciers in the Beas river basin are quite similar to the changes in Chhota Shigri glacier during 2000-2011 in general, although there is variability both in independent glacier and over the region. Furthermore, in our study basin, the glaciological mass balance series published in Spiti-Lahaul region (of HMA) available for comparison, are the Chhota Shigri glacier and Bara Shigri glacier (Berithier et al. 2007). In which, the only one is long enough to be comparable to our simulation period is the Chhota Shigri glacier (2002-2014), which also has geodetic mass balance for validation (Azam et al. 2016). So we used the mass balance data of Chhota Shigri glacier as a representation for the glaciers in our small basin (see Fig. 1 and Table 4). In the calibration, we firstly 'pre-calibrate' all parameters according to the observed discharge data of Thalout station. Secondly, we manually adjusted the parameters of glacier module according to the observed annual glacier mass balance data in Table 4, which is from previous studies (Berthier et al. 2007; Wagnon et al., 2007; Vincent et al. 2013; Azam et al. 2014, 2016). Then, all parameters except the glacier module parameters were re-calibrated according to discharge data at the very last time. The calibration and validation period in this study were 1986-2000 and 2001-2004, respectively. We used the data of 1986 for three preceding spin-up years. All the calibration and validation results of glacier mass balance in the study are listed in Table 4. In the study, we used 1986-2004 period (2005 was included in the calibration and simulation of bias correction) for glacier and hydrological calibration and validation, because those are the periods fit to the available glacier mass balance data from previous studies. In the calibration, GSM-WASMOD run with the 5000 parameter sets, which were obtained by the Latin-Hypercube sampling method (Gong et al., 2009, 2011; Li et al., 2015a). The best parameter set was then chosen based on three indices, including Nash-Sutcliffe coefficient (NSC), relative volume error (VE) and root-mean-square error (RMSE). For the best model performance, the NSC is to be 1 and the other two indices, i.e., VE and RMSE, are to be 0.

4 RESULTS

4.1 Corrected Precipitation

The uncorrected and corrected mean annual precipitation (1986-2004) are 1213 mm/yr and 1374 mm/yr, respectively. The calibration results (1986-2000) show that the daily NSC driving by uncorrected and corrected precipitation is 0.64 and 0.65, respectively (Table 5). The RMSE, VE and monthly NSC from the calibration of GSM-WASMOD driving by the corrected precipitation are 2.01, 7% and 0.75, respectively, while those by uncorrected precipitation are 2.03, 8% and 0.70, respectively. It shows an improvement of all indices in both calibration and validation from the corrected precipitation comparing with that from uncorrected precipitation. The results confirmed that there is much heavier precipitation at high altitude in Himalaya regions than what we knew from the gauge data and other gridded data set. The high-resolution precipitation of RCM, i.e., WRF, has the potential to provide more information and knowledge for the high altitude precipitation in Himalaya region, although it still has challenges in capturing the precipitation variability accurately at high-resolution spatial scale (i.e., complex topography) and temporal scale (i.e., daily or hourly).

4.2 GSM-WASMOD model calibration and validation

The calibration (1986-2000) and validation (2001-2004) results from WASMOD and GSM-WASMOD are given in Table 5, which shows that GSM-WASMOD has improved the performance of WASMOD in reproducing historical discharge in Beas river basin. For example, for the GSM-WASMOD modeling, the daily NSC and monthly NSC in the calibration are 0.65 and 0.75 respectively, which are 0.61 and 0.66 respectively in the validation. While for the WASMOD model, the daily NSC and monthly NSC in calibration are 0.50 and 0.65 respectively, which are only 0.31 and 0.36 in the validation. It shows that the GSM-WASMOD performs more reliably than WASMOD comparing the results from both calibration and validation. Furthermore, the precipitation correction has improved the modeling performance in Beas river basin, especially regarding the results of model validation. For the Beas river basin, located to North mountainous India, the model underestimates the flow during June-August, which leads to a large negative bias (Fig. 3). The mean annual un-corrected precipitation and corrected precipitation is 1213 mm/yr and 1374 mm/yr of 1986-2004, while the observed discharge of 1284 mm/yr is even larger than the uncorrected precipitation. The bias is most likely related to an underestimation of precipitation due to limited rain gauge stations, although we did precipitation correction over high mountain area in winter period. In Fig. 4, the total discharge includes fast-flow and slow-flow from the non-glacier area and discharge from the glacier area, which includes rainfall discharge, snow-melt and ice-melt discharge. The fast-flow is generally considered to be the surface runoff and the slow-flow refers to base-flow.

The Chhota Shigri glacier is the only one which has been well studied and has detailed and longer period of glacier mass balance data in the Spiti-Lahaul region where Beas river basin locates. The Chhota Shigri Glacier is a part of the Chandra Basin, which is a sub-basin of the Chenab river basin (Ramanathan, 2011), but it is attached to northeast boundary of Beas river basin, which is close to Manali and Bhunter stations (Fig.1). In this case, the glacier mass balance of Chhota Shigri Glacier is used for glacier module calibration in the study, which is to be comparable to the simulation. The total runoff (including rainfall discharge, ice-melt and snow-melt discharge) from glacier cover area contribute about 19 % of total runoff and the glacier imbalance is about 5 % of total runoff in Beas River basin up to Thalout station during 1986-2004. The monthly hydrography of ice and snow melt discharge, total glacier area discharge, and simulated and observed discharges during the calibration and validation period are shown in Fig. 5. For validation of the model results on glacier mass balance, we compared our results to the previous studies (Table 4 and Fig. 6). For example, the simulated annual glacier mass balance of Beas river is -0.22 m w.e. a^{-1} of 1986-2000 in our simulation, which is comparable to the results of the modelled annual glacier mass balance of Chhota Shigri glacier (1986-2000), which is -0.01 (+/-0.36) m w.e. a^{-1} by Azam et al. (2014) and -0.29 (+/-0.33) m w.e. a^{-1} by Engelhardt et al.(2017). Besides, the annual glacier mass balance is -1.09 m w.e. a^{-1} of 1999-2004 from our study, which is also similar with the results from the other two previous studies, i.e., the measured annual glacier mass balance (1999-2004) of Chhota Shigri glacier is -1.02 or -1.12 m w.e. a^{-1} from geodetic measured by Berthier et al. (2007) and -1.03(+/- 0.44) m w.e. a^{-1} by Vincent et al. (2013). Considering the uncertainties in the meteorological forcing data and high complexity in the hydrological cycle over high altitude Himalaya mountainous area, the model is considered to be satisfactory for estimating the impacts of climate change for the future Beas's water.

4.3 Evaluation of LOCI and DBC

The performance of LOCI and DBC in correcting precipitation and temperature is evaluated using two common statistics over the historical period (1986-2005): mean and standard deviation. Fig. 7 shows an example of evaluation results of corrected precipitation and temperature at the Pandoh station. The figure shows that GCM-simulated precipitation and temperature are considerably biased concerning reproducing the mean and standard deviation. Both LOCI and DBC are capable of reducing the bias of mean and standard deviation of precipitation and temperature at the reference period, even though there are some uncertainties related to GCMs. However, DBC performs much better than LOCI at reproducing the standard deviation of precipitation, which is expected, because the standard deviation of precipitation was not specifically considered in LOCI. In other words, LOCI only corrected the mean of monthly precipitation. However, this is not the case of DBC, as it corrected the distribution shape of precipitation. The standard deviation was corrected along with the mean. For temperature, both LOCI and DBC can remove biases of mean and standard deviations for the reference period. Above evaluation results indicate the reasonable performance of both bias correction methods. The precipitation in Fig. 7 is un-corrected precipitation from DBC and LOCI, which are different from the precipitation in Fig. 8 that shows the corrected precipitation (based on the precipitation correction method in section 3.5).

4.4 Future climate change

The climate change scenarios for GSM-WASMOD simulation are illustrated in Table 2. The changes of mean monthly precipitation and temperature of the Beas river basin in the early future (2046-2065) and the late future (2080-2099) compared with the baseline period (1986-2005) are shown in Fig. 8 and Fig. 9. In general, the temperatures from DBC and LOCI are all shown increasing for all scenarios for the both early and later future; while there is more uncertainty in precipitation change in the future. It is consistent with the annual precipitation and temperature changes of the Beas river basin, which are shown in Fig. 10. From the figure, we can see that under Climate change impact, the study area will be getting warmer. The uncertainty of temperature increase in the late future is much larger than that from early future, while for the future change of precipitation, both early and late future have a widespread uncertainty, especially by LOCI method. It is worth to point out that the winter precipitation (December -March) in Fig. 8 is much higher than that from Fig. 7. This is because the precipitation correction has made in Fig. 8. A more detailed statistical analysis result is shown in Table 6, which is based on the corrected precipitation. The annual mean temperature of Beas river basin is approximately warm up to ~1.8°C (RCP4.5) and ~2.8 °C (RCP8.5) in the middle of the century (2046-2065) comparing with baseline period (1986-2005), and up to ~2.3 °C (RCP4.5) and ~5.4 °C (RCP8.5) at the end of the century (2080-2099) comparing with the same baseline period. For the annual mean precipitation, the change will be +9.8 % (RCP4.5) and +33.3 % (RCP8.5) in the middle of the century (2046-2065) comparing with the baseline period (1986-2005), and +17.7 % (RCP4.5) and +39.7 % (RCP8.5) in Beas river basin at the end of the century (2080-2099). However, there is a similar widespread of uncertainty in precipitation increase from LOCI as DBC. While for the temperature increase, the uncertainty spread of temperature increase from DBC is much wider than that from LOCI, especially under RCP85 for late future (2080-2099). It is very likely that the Beas river basin will get warmer and wetter compared to the historical period, which are also confirmed by other studies (e.g., Aggarwal et al., 2016; Ali et al., 2015). Under DBC RCP8.5, the temperature increases the most, while for precipitation, the LOCI RCP8.5 increases most.

4.5 Future glacier extent change

The projected changes in glacier extent in the Beas river basin under eight climate change scenarios are shown in Fig. 11. Unsurprisingly, the glacier extent will keep retreating in the future at Beas river basin. There are large uncertainties in the changes of the glacier extent from different projections (Fig. 11), which are confirmed by other studies (e.g., Kraaijenbrink et al., 2017, Lutz et al., 2016; Li et al. 2016). In this study, the glacier extent in the Beas river basin is projected to decrease over the range of 63 - 81 % (RCP4.5) and 76 - 87 % (RCP8.5) by the middle of the century (2050) and 89 - 99 % (RCP4.5) and 93 - 100 % (RCP8.5) at the end of the century (2100) compared to the glacier extent in 2005. The range in the projections is comparable for both statistical downscaling methods. The rapid decrease in glacier extent is mainly driven by strong temperature increase, which cannot be compensated by an increase in precipitation. In the Beas river basin, approximately 90%

of the glacier surfaces is located between 4500 and 5500 m a.m.s.l. This relatively small altitudinal range may be another reason for the rapid retreat.

4.6 Future Hydrological changes

There is a consistent trend of projected hydrological changes over all the scenarios, although there are large uncertainties. The glacier discharge is projected to decrease over the century across all the scenarios led by the glacier extent decrease (Fig. 12), while the future change of total discharge over Beas river basin is not that clear in Fig. 13. This is most likely because of the increase in both precipitation and temperature throughout the whole 21st century. There is a wide spreading of glacier ablation near the middle of the century, which indicates a larger uncertainty in the prediction discharge over this period. Table 6 provides more details of the change of glacier extent, precipitation, temperature, discharge and evaporation (ET) in Beas river basin in the middle of the century (2046-2065) and at the end of the century (2080-2099) comparing with the historical baseline period (1986-2005). There are large ranges in different climate change scenarios. The future delta change of (future minus baseline) and future predicted mean monthly evaporation and discharge over Beas river basin up to Pandoh are shown in Fig. 14 and Fig. 15. According to those two figures, we can see that (1) the projected discharge will increase in general especially in winter and pre-monsoon under both RCP4.5 and RCP8.5 for near future (2045-2055) and far future (2080-2099); (2) under RCP8.5, there is a slight decrease in discharge can be seen from the mean results of DBC during monsoon season, especially in July, also with the largest uncertainty comparing with other seasons. One of the main reasons for this decrease of summer discharge is probably the significant glacier retreating under the future climate; (3) the largest change of discharge can be observed in July for near future (2046-2065), which also has the widest range, i.e., from -99 mm to over 265 mm by LOCI and from -120 mm to 108 mm by DBC; (4) for the late future (2080-2099), the widest discharge change can be observed in August, which is from -117 mm to 309 mm by LOCI method and from around -145 mm to over 228 mm by DBC method. This is probably due to both the glacier extent decrease and the temperature increase. The uncertainty of projected discharge under RCP8.5 is much larger than that under RCP4.5; (5) for the evaporation, a general increase can be seen all over the year from both LOCI and DBC; (6) the largest increase of evaporation will be in April, with also the largest spread, i.e., around 5 ~ 26 mm and 1 ~ 26 mm by LOCI and DBC, respectively. This large evaporation increase most likely is driven by the increase of both precipitation and glacier melting regarding increased temperature, which will provide a much wetter environment in the future than the historical periods.

5 DISCUSSIONS

5.1 Uncertainty of high mountain precipitation

There are many uncertainties and challenges for the future hydrological projection under climate change in the Beas river basin. The dedication of snow and glacier melting is significant for the total runoff, which varies from 27.5 % ~ 40% by previous studies (e.g., Kumar et al. 2007; Li et al. 2013a, 2015a). In our study, the total snow and glacier melting from the glacier-covered area is 19% of the total runoff, and the glacier retreat is accounting for round 5% during 1986-2004, which is comparable with the same value of 5% during 2003-2008 by Kääb et al. (2015), who used ICESat satellite altimetry data. There are several reasons for this large spread of percentage of snow and glacier melting in the Beas river basin. Most common knowledge of one of the challenges in high mountain area is the data issue. A large disagreement between precipitation from dynamical RCM simulations (WRF) and other data sources (i.e., TRMM 3B42 V7, APHRODITE and gauge data) were found over high altitude in the Beas river basin by the previous study of Li et al. (2017). There are no gauge stations over 2000 m a.m.s.l. in our study, and neither of the gauge stations includes appropriate snowfall measurement. Lacking of reliable snowfall measurement over the Himalaya regions is one of the reasons for a poor understanding and a large uncertain of high altitude precipitation over this area (Mair et al., 2013; Ragettli and Pellicciotti, 2012; Immerzeel et al., 2013, 2015; Viste and Sorteberg, 2015; Ji et al., 2015; Dahri et al., 2016). Some previous studies showed that the high altitude precipitation is much larger than previously thought and other datasets (Immerzeel et al., 2015; Li et al., 2017; Dahri et al., 2016). Dahri et al. (2016) applied a geo-statistical analysis of precipitation observations revealed substantially higher precipitation in most of the sub-basins compared to earlier studies and they pointed out that the uncorrected gridded precipitation products are highly unsuitable to estimate precipitation distribution and to drive glacio-hydrological models in water balance studies in the high-altitude areas of Indus basin. Comparison of the high-resolution WRF precipitation with gauge rainfall showed an underestimation of WRF at Manali station in the summer period (July-September). The Manali precipitation is more heavily influenced by the complex topography than other stations because it locates at a bit deeper valley in the mountains. This is probably the main reason that WRF underestimates the rainfall in summer period comparing with gauge rainfall. While for winter period (December-March), the WRF results showed much larger precipitation over high altitude in Beas river basin comparing with gauge rainfall. Although we did precipitation correction based on this high-resolution WRF precipitation, which improved results for both calibration and validation in the study, the real amount of precipitation over Himalayan region, like Beas river basin, is still uncertain.

5.2 Uncertain future of glacio-hydrological changes in Beas river basin

In our study, the results show a large uncertainty in the future river flow changes over the Beas river basin up to Pandoh among all the future scenarios, although the glacier is retreating from all the scenarios. From the results, we can see that there are differences (i.e., seasonal change and hydrological element's variability) from those two BC methods, i.e., LOCI and DBC, although in general, the annual changes of the main variables in hydrological cycle are similar from those two BC methods. For example, the discharge during the monsoon period (June-August) is likely to decrease, although it varies a lot within the impact of all the GCMs, RCP and BC methods. The main decrease is found in July from DBC, while a slight increase can be seen from the mean of LOCI. Besides, the peak flow in the middle of the century is slightly shifted to be early in July from the LOCI, which confirmed the study result from Lutz et al. (2016), while this change cannot be seen in the results from DBC. In general, the future runoff over Beas river basin is likely to increase slightly, especially in the winter and pre-monsoon period, with large uncertainty in the summer period. The results are consistent with some previous studies. For instance, the future river flow in the Beas river basin was projected to be increasing for the future periods (during 2006 ~ 2100) compared with the baseline period of 1976-2005 by Ali et al. (2015). In their study, however, the future hydrological simulation was lacking glacier component, which did not account for glacier retreat under future climate change impact. In the other study of Li et al. (2016), a large spread of river flow changes from different scenarios can be seen, and no uniform conclusion can be conducted from their projections. Furthermore, there is an obvious evaporation decrease in September from DBC method, which cannot be seen from the LOCI method. From our study, we can see that the uncertainty of future hydrological change comes not only from GCMs but also from the two bias correction methods.

There are several limitations of this study that need to be addressed. Firstly, only two bias correction methods were used in the study. According to the previous studies, bias correction results in physical inconsistencies since the corrected variables are not independent of each other (Ehret et al., 2012; Immerzeel et al., 2013). For instance, although bias corrected precipitation data will improve the hydrological calibration results, it will no longer be consistent with modeled other variables, e.g., temperature, radiation. It is generally based on the assumption of stationary climate distribution regarding the variance and skewness of the distribution, which however is crucial for assessing the impact of climate change on seasonality and extremes of the hydrological cycle. More ensemble statistical downscaling methods are needed for predicting future river flows to include enough uncertainties and to have a better picture of the robust future hydrological impact assessment. Secondly, the simplification of glacier module, especially without considering the effect of debris, will also result in uncertainty in the results (Scherler et al., 2011; Azam et al., 2018). Furthermore, the limitations of data, e.g., sparsely rainfall stations and no snowfall measurement, in such high-mountain drainage basin also lead to considerable uncertainty in hydrological simulation, and this is a common challenge for modeling study in this region.

6 CONCLUSIONS

An integrated glacio-hydrological model: Glacier and Snow Melt - WASMOD model (GSM-WASMOD) was applied for investigating the hydrological projection under climate change during the 21st century in the Beas basin. The river flow is impacted by the glacier melt. The glacier extent evolutions under climate change were estimated by a basin-scale regionalized glacier mass balance model with parameterization of glacier area changes, which were used in the study for constructing the future glacier extent scenarios in the GSM-WASMOD model for investigating the hydrological response of Beas river basin up to Pandoh. The changes of precipitation, temperature, runoff and evaporation in Beas river basin in the early future (2046-2065) and the late future (2080- 2099) were investigated in the study.

A high-resolution WRF precipitation suggested much higher winter precipitation over high altitude area in the Beas river basin than we knew from the gauge data and other available gridded datasets, which was used for precipitation correction in our study. The results indicate that the corrected precipitation is more reliable and performs better in both the calibration and validation of GSM-WASMOD in the Beas river basin, compared with the uncorrected precipitation. Besides, the calibration and validation based on both glacier mass balance and discharge show that GSM-WASMOD, which although has only a conceptual glacier module, performs much better than the early version of WASMOD. Furthermore, the results reveal that the glacier imbalance of -0.4 (-1.8 ~ +0.6) m w.e. a^{-1} is about 5 % of total runoff during 1986-2004 in Beas River basin up to Thalout station at present (1990-2004).

Under Climate change impact, the temperature will increase by 1.8 °C (RCP4.5) and 2.8 °C (RCP8.5) for the early future (2046-2065), and increase by 2.3 °C (RCP4.5) and 5.4°C (RCP8.5) at the late future (2080-2099), while the precipitation will increase by 9.8 % (RCP4.5) and 33.3 % (RCP4.5) for the early future, and increase by 17.7 % (RCP4.5) and 39.7 % (RCP8.5) for the late future over the Beas river basin. However, there is a large uncertainty spread during different future scenarios based on the impact of GCMs and RCPs. The glacier extent loss is about 73 % under RCP4.5 scenario and 81 % under RCP8.5 scenario at the early future and 94 % under RCP4.5 scenario and 99 % under RCP8.5 scenario at the late future, which results in a loss of discharge in monsoon period. There was a broad spread of evaporation and discharge change in the Beas river basin in the future scenarios. The runoff was projected to have a slight increase from the mean of all the future scenarios, although the changes vary with seasons and have a large uncertainty. The precipitation increase and glacier retreat make a complex future of total discharge with a general increase in winter and pre-monsoon period, while considerable uncertainty can be seen in monsoon period, i.e., a discharge decrease in July from DBC and discharge increase from LOCI. Besides, there is a drop in evaporation in September from DBC, which cannot be seen from LOCI. The peak flow in the middle of the century is slightly shifted to be early in July from LOCI, while this change cannot be seen in the results from DBC. It indicates that the uncertainty of future hydrological change comes not only from GCMs but also from the two bias correction methods. Furthermore, the Beas river basin is very likely to become warmer and wetter in both the early and late future, although large uncertainties in the study of future water under climate change can be seen.

ACKNOWLEDGMENTS

This study was jointly funded by the Research Council of Norway (RCN) project 216576 (NORINDIA), project-JOINTINDNOR 203867, project GLACINDIA 033L164 and project EVOGLAC 255049.

References

Aggarwal, S.P., Thakur, P.K., Garg, V., Nikam, B.R., Chouksey, A., Dhote, P. and Bhattacharya, T., 2016. Water resources status and availability assessment in current and future climate change scenarios for beas river basin of north western himalaya. International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, 40.

Akhtar, M., Ahmad, N. & Booij, M. J. 2008. The impact of climate change on the water resources of Hindukush-Karakorum-Himalaya region under different glacier coverage scenarios. *Journal of Hydrology,* 355**,** 148-163.

Ali, D., Sacchetto, E., Dumontet, E., LE Carrer, D., Orsonneau, J. L., Delaroche, O. & Bigot-Corbel, E. 2014. Hemolysis influence on twenty-two biochemical parameters measurement. *Annales De Biologie Clinique,* 72**,** 297-311.

Ali, S., Dan, L., Fu, C. B. & Khan, F. 2015. Twenty first century climatic and hydrological changes over Upper Indus Basin of Himalayan region of Pakistan. *Environmental Research Letters,* 10.

Anand, J., Devak, M., Gosain, A. K., Khosa, R., and Dhanya, C. T., 2017. Spatial Extent of Future Changes in the Hydrologic Cycle Components in Ganga Basin using Ranked CORDEX RCMs, Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-189, in review.

Azam, M.F., Wagnon, P., Vincent, C., Ramanathan, A., Linda, A. and Singh, V.B., 2014. Reconstruction of the annual mass balance of Chhota Shigri glacier, Western Himalaya, India, since 1969. Annals of Glaciology, 55(66), pp.69-80.

Azam, M.F., Ramanathan, A.L., Wagnon, P., Vincent, C., Linda, A., Berthier, E., Sharma, P., Mandal, A., Angchuk, T., Singh, V.B. and Pottakkal, J.G., 2016. Meteorological conditions, seasonal and annual mass balances of Chhota Shigri Glacier, western Himalaya, India. *Annals of Glaciology*, *57*(71), pp.328-338.

Azam, M.F., Wagnon, P., Berthier, E., Vincent, C., Fujita, K. and Kargel, J.S., 2018. Review of the status and mass changes of Himalayan-Karakoram glaciers. *Journal of Glaciology*, *64*(243), pp.61-74.

Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P. and Chevallier, P., 2007. Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India). Remote Sensing of Environment, 108(3), pp.327-338.

Berthier, E. 2006. GLIMS Glacier Database. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. Digital Media.

Bolch, T., A. Kulkarni, A. Kääb, C. Huggel, F. Paul, J.G. Cogley, H. Frey, J.S. Kargel, K. Fujita, M. Scheel, S. Bajracharya, M. Stoffel. 2012. The state and fate of Himalayan glaciers. Science, 336, pp. 310–314

Biskop, S., Krause, P., Helmschrot, J., Fink, M., & Flügel, W. A., 2012. Assessment of data uncertainty and plausibility over the Nam Co Region, Tibet. Advances in Geosciences, 31, 57-65.

Brun, F., Berthier, E., Wagnon, P., Kääb, A. and Treichler, D., 2017. A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. Nature geoscience, 10(9), pp.668-673.

Cannon, A.J., Sobie, S.R. and Murdock, T.Q., 2015. Bias correction of GCM precipitation by quantile mapping: How well do methods preserve changes in quantiles and extremes? *Journal of Climate*, *28*(17), pp.6938-6959.

Chen, H., Xu, C.Y. and Guo, S., 2012. Comparison and evaluation of multiple GCMs, statistical downscaling and hydrological models in the study of climate change impacts on runoff. Journal of hydrology, 434, pp.36-45.

Chen, H., Guo, J., Xiong, W., Guo, S.L., Xu, C.Y., 2010. Downscaling GCMs using the Smooth Support Vector Machine method to predict daily precipitation in the Hanjiang Basin. Adv. Atmos. Sci. 27 (2), 274®C284.

Chen, J., Brissette, F.P., Leconte, R., 2011. Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. J. Hydrol. 401, 190–202.

Chen, J., Brissette, F.P., Chaumont, D. and Braun, M., 2013. Performance and uncertainty evaluation of empirical downscaling methods in quantifying the climate change impacts on hydrology over two North American river basins. *Journal of Hydrology*, *479*, pp.200-214.

Chu, J. T., Xia J., and Xu C. Y., 2010. Statistical downscaling of daily mean temperature, pan evaporation and precipitation for climate change scenarios in Haihe River, China. Theor. App. Climatol., 99(1-2), 149–161, doi:10.1007/s00704-009-0129-6.

Collier, E., Mölg, T., Maussion, F., Scherer, D., Mayer, C., & Bush, A. B. G., 2013. High-resolution interactive modelling of the mountain glacier–atmosphere interface: an application over the Karakoram. The Cryosphere Discussions, 7(1), 103-144.

Dahri, Z. H., Ludwig, F., Moors, E., Ahmad, B., Khan, A. and Kabat, P., 2016. An appraisal of precipitation distribution in the high-altitude catchments of the Indus basin, Sci. Total Environ., 548–549, 289–306, doi:10.1016/j.scitotenv.2016.01.001.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., ... & Vitart, F., 2011. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137(656), 553-597.

Dibike, Y., and Coulibaly P., 2005. Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. J. Hydrol. 307(1-4), 145–163, doi:10.1016/j.jhydrol.2004.10.012.

Dimri, A. P., Yasunari, T., Wiltshire, A., Kumar, P., Mathison, C., Ridley, J., and Jacob, D., 2013. Application of regional climate models to the Indian winter monsoon over the western Himalayas, Sci. Total Environ., online first, doi:10.1016/j.scitotenv.2013.01.040.

Engelhardt, M., Schuler, T. V. & Andreassen, L. M., 2012. Evaluation of gridded precipitation for Norway using glacier mass-balance measurements. Geogr. Ann. A 94, 501–509, doi: 10.1111/j.1468-0459.2012.00473.x.

Engelhardt, M., Ramanathan, A.L., Eidhammer, T., Kumar, P., Landgren, O., Mandal, A. and Rasmussen, R., 2017. Modelling 60 years of glacier mass balance and runoff for Chhota Shigri Glacier, Western Himalaya, Northern India. Journal of Glaciology, 63(240), pp.618-628.

Eden, J.M., Widmann, M., Maraun, D. and Vrac, M., 2014. Comparison of GCM-and RCM-simulated precipitation following stochastic postprocessing. *Journal of Geophysical Research: Atmospheres*, *119*(19), pp.11-040.

Fang, G., Yang, J., Chen, Y.N. and Zammit, C., 2015. Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences*, *19*(6), pp.2547-2559.

Fiseha, B.M., Setegn, S.G., Melesse, A.M., Volpi, E. and Fiori, A., 2014. Impact of climate change on the hydrology of upper Tiber River Basin using bias corrected regional climate model. *Water resources management*, *28*(5), pp.1327-1343.

Fujihara, Y., Tanaka, K., Watanabe, T., Nagano, T. and Kojiri, T., 2008. Assessing the impacts of climate change on the water resources of the Seyhan River Basin in Turkey: Use of dynamically downscaled data for hydrologic simulations. *Journal of Hydrology*, *353*(1-2), pp.33-48.

Gardelle, J., Berthier, E., Arnaud, Y. and Kääb, A., 2013. Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011, Cryosph., 7(4), 1263–1286.

Gong, L., Widen-Nilsson, E., Halldin, S. and Xu, C.Y., 2009. Large-scale runoff routing with an aggregated network-response function. *Journal of Hydrology*, *368*(1-4), pp.237-250.

Gong, L., Halldin, S. & Xu, C-Y., 2011. Global scale river routing—an efficient time delay algorithm based on HydroSHEDS high resolution hydrography. Hydrol. Processes 25(7), 1114–1128.

Hartmann, H. and Andresky, L., 2013. Flooding in the Indus River basin – a spatiotemporal analysis of precipitation records, Global Planet. Change, 107, 25–35.

Hasson, S., Lucarini, V., Khan, M.R., Petitta, M., Bolch, T., Gioli, G., 2014. Early 21st century snow cover state over the western river basins of the Indus River system. Hydrol. Earth Syst. Sci. 18, 4077–4100. http://dx.doi.org/10.5194/hess-18-4077-2014.

Hasson, S., 2016. Future Water Availability from Hindukush-Karakoram-Himalaya upper Indus Basin under Conflicting Climate Change Scenarios. Climate, 4(3), p.40.

Hessami M, Gachon P, Ouarda TBMJ, St-Hilaire A., 2008. Automated regression-based statistical downscaling tool. Environmental Mod- elling and Software 23: 813–834.

Hewitt. K., 2005. The Karakoram anomaly? Glacier expansion and the 'elevation effect', Karakoram Himalaya Mountain Research and Development, 25, pp. 332–340

Hock, R., 2003. Temperature index modelling in mountain areas. J. Hydrol. 282(1–4), 104–115.

Huffman, G. J., Adler, R. F., Bolvin, D. T., Gu, G., Nelkin, E. J., Bowman, K .P., Hong, Y., Stocker, E. F., and Wolff, D. B., 2007. The TRMM multi-satellite precipitation analysis: Quasi-global, multi-year, combined-sensor precipitation estimates at fine scale, J. Hydrometeor., 8(1), 38–55.

Horton, P., Schaefli, B., Mezghani, A., Hingray, B. and Musy, A., 2006. Assessment of climate-change impacts on alpine discharge regimes with climate model uncertainty. *Hydrological Processes: An International Journal*, *20*(10), pp.2091-2109.

Immerzeel, W.W., Wanders, N., Lutz, A.F., Shea, J.M. and Bierkens, M.F.P., 2015. Reconciling high-altitude precipitation in the upper Indus basin with glacier mass balances and runoff. Hydrology and Earth System Sciences, 19(11), p.4673.

Immerzeel, W., Pellicciotti, F., and Bierkens, M., 2013. Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds, Nat. Geosci., 6, 742–745, doi:10.1038/NGEO1896, 4757, 4761, 4773.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G. and Georgopoulou, E., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, *14*(2), pp.563-578.

Ji, Z.M. and Kang, S.C., 2015. Evaluation of extreme climate events using a regional climate model for China. International Journal of Climatology, 35(6), pp.888-902.

Ji, Z.M., Kang, S.C., 2013. Projection of snow cover changes over China under RCP scenarios. Climate Dynamics, 41, 589-600.

Johnson, F. and Sharma, A., 2015. What are the impacts of bias correction on future drought projections? *Journal of Hydrology,* 525**,** 472-485.

Kattel, D.B., Yao, T., Yang, K., Tian, L., Yang, G. and Joswiak, D., 2013. Temperature lapse rate in complex mountain terrain on the southern slope of the central Himalayas. Theoretical and applied climatology, 113(3-4), pp.671-682.

Kääb, A., Treichler, D., Nuth, C. and Berthier, E., 2015. Brief Communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya. The Cryosphere, 9(2), pp.557-564.

Khan, F., Pilz, J., Amjad, M. and Wiberg, D. A., 2015. Climate variability and its impacts on water resources in the Upper Indus Basin under IPCC climate change scenarios. *International Journal of Global Warming,* 8**,** 46-69.

Kraaijenbrink, PDA, Bierkens, MFP, Lutz, A.F., and Immerzeel, W.W., 2017. Impact of a 1.5 °C global temperature rise on Asia's glaciers. Nature 549:257–260.

Kumar, V., Singh, P. and Singh, V., 2007. Snow and glacier melt contribution in the Beas River at Pandoh Dam, Himachal Pradesh, India. *Hydrological sciences journal,* 52**,** 376-388.

Li, L., Engelhard M., Xu, C.Y., JAIN, S.J., Singh, V.P., 2013a. Comparison of satellite-based and reanalysed precipitation as input to glacio-hydrological modeling for Beas river basin, Northern India. Cold and Mountain Region Hydrological Systems Under Climate Change: Towards Improved Projections. IAHS Publ. 360. 45-52.

Li, L., Ngongondo, C. S., Xu, C. Y., and Gong, L. ,2013b. Comparison of the global TRMM and WFD precipitation datasets in driving a large-scale hydrological model in Southern Africa. Hydrol Res. doi, 10, 2166.

Li, H., Xu C-Y, Beldring S, Tallaksen TM, Jain SK, 2016. Water Resources under Climate Change in Himalayan basins. Water Resources Management 30:843–859. DOI:10.1007/s11269-015-1194-5.

Li, H., Beldring, S., Xu, C-Y, Huss, M., Melvold, K., 2015a. Integrating a glacier retreat model into a hydrological model -- case studies on three glacierised catchments in Norway and Himalayan region. Journal of Hydrology 527, 656-667. doi:10.1016/j.jhydrol.2015.05.017.

Li, L., Diallo, I., Xu, C-Y, Stordal, F., 2015b. Hydrological projections under climate change in the near future by RegCM4 in Southern Africa using a large-scale hydrological model. Journal of Hydrology 528, 1-16, doi:10.1016/j.jhydrol.2015.05.028.

Li, L., Gochis, D.J., Sobolowski, S. and Mesquita, M.D., 2017. Evaluating the present annual water budget of a Himalayan headwater river basin using a high-resolution atmosphere-hydrology model. Journal of Geophysical Research: Atmospheres, 122(9), pp.4786-4807.

Lutz, A., Immerzeel, W.W., Gobiet, A., Pellicciotti, F. and Bierkens, M.F.P., 2013. Comparison of climate change signals in CMIP3 and CMIP5 multi-model ensembles and implications for Central Asian glaciers. *Hydrology and Earth System Sciences*, *17*, pp.3661-3677.

Lutz, A.F., Immerzeel, W.W., Shrestha, A.B. and Bierkens, M.F.P., 2014. Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, *4*(7), p.587.

Lutz, A.F., Immerzeel, W.W., Kraaijenbrink, P.D.A., Shrestha, A.B. and Bierkens, M.F., 2016. Climate change impacts on the upper Indus hydrology: Sources, shifts and extremes. *PloS one*, *11*(11).

Maussion, F., Scherer, D., Finkelnburg, R., Richters, J., Yang, W. and Yao, T., 2011. WRF simulation of a precipitation event over the Tibetan Plateau, China--an assessment using remote sensing and ground observations. *Hydrology & Earth System Sciences*, *15*(6).

Mair, E., Bertoldi, G., Leitinger, G., Chiesa, S. D., Niedrist, G., & Tappeiner, U., 2013. ESOLIP–estimate of solid and liquid precipitation at sub-daily time resolution by combining snow height and rain gauge measurements. *Hydrology and Earth System Sciences Discussions*, *10*(7), 8683-8714.

Ménégoz, M., Gallée, H., & Jacobi, H. W., 2013. Precipitation and snow cover in the Himalaya: from reanalysis to regional climate simulations. Hydrology and Earth System Sciences, 17(10), 3921-3936.

Mishra, V., 2015. Climatic uncertainty in Himalayan water towers. *Journal of Geophysical Research: Atmospheres*, *120*(7), pp.2689-2705.

Mitchell, T. D. and Jones, P. D., 2005. An improved method of construct- ing a database of monthly climate observations and associated high-resolution grids, Int. J. Climatol., 25, 693–712, 2005.

Mpelasoka, F.S., Chiew, F.H.S., 2009. Influence of rainfall scenario construction methods on runoff projections. J. Hydrometeorol. 10, 1168–1183.

Palazzi, E., Hardenberg, J. Von and Provenzale, A., 2013. Precipitation in the Hindu-Kush Karakoram Himalaya : Observations and future scenarios, J. Geophys. Res. Atmos., 118, 85–100.

Pechlivanidis, I.G., Arheimer, B., Donnelly, C., Hundecha, Y., Huang, S., Aich, V., Samaniego, L., Eisner, S. and Shi, P., 2017. Analysis of hydrological extremes at different hydro-climatic regimes under present and future conditions. *Climatic Change*, *141*(3), pp.467-481.

Ramanathan, AL., 2011. Status Report on Chhota Shigri Glacier (Himachal Pradesh), Department of Science and Technology, Ministry of Science and Technology, New Delhi. Himalayan Glaciology Technical Report No.1,pp-88p.

Rasmussen, R., Liu, C., Ikeda, K., Gochis, D., Yates, D., Chen, F., ... & Gutmann, E., 2011. High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: a process study of current and warmer climate. *Journal of Climate*, *24*(12), 3015-3048.

Rasmussen, R.M., K. Ikeda, C. Liu, D.J. Gochis, M. Clark, A. Dai, E. Gutmann, J. Dudhia, F. Chen, M.J. Barlage, D. Yates, and G. Zhang, 2014. Climate change impacts on the water balance of the Colorado headwaters: High-resolution regional climate model simulations. Journal of Hydrometeorology, 15, 1091-1116.

Raup, B. H., Racoviteanu, A., Khalsa, S. J. S., Helm, C., Armstrong, R. & Arnaud Y. (2007) The GLIMS Geospatial Glacier Database: a new tool for studying glacier change. Global Planetary Change 56, 101–110. (doi:10.1016/j.gloplacha.2006.07.018).

Ragettli, S. and Pellicciotti, F., 2012. Calibration of a physically based, spatially distributed hydrological model in a glacierized basin: on the use of knowledge from glaciometeorological processes to constrain model parameters, Water Resour. Res., 48, 1–20.

RGI Consortium, 2017. Randolph Glacier Inventory – A Dataset of Global Glacier Outlines: Version 6.0: Technical Report, Global Land Ice Measurements from Space, Colorado, USA. Digital Media. DOI: https://doi.org/10.7265/N5-RGI-60

Rudd, A.C., A. L. and Kay, 2016. Use of very high resolution climate model data for hydrological modelling: estimation of potential evaporation. Hydrol. Res., 47(3), 660-670, doi:10.2166/nh.2015.028.

Samaniego, L., Kumar, R., Breuer, L., Chamorro, A., Flörke, M., Pechlivanidis, I.G., Schäfer, D., Shah, H., Vetter, T., Wortmann, M. and Zeng, X., 2017. Propagation of forcing and model uncertainties on to hydrological drought characteristics in a multi-model century-long experiment in large river basins. *Climatic change*, *141*(3), pp.435-449.

Scherler D, Bookhagen B and Strecker MR.., 2011. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nat. Geosci., 4, 156–159.

Schmidli, J., Frei, C., Vidale, P.L., 2006. Downscaling from GCM precipitation: a benchmark for dynamical and statistical downscaling methods. Int. J. Climatol. 26, 679–689.

Singh, P., Kumar, N. and Arora, M., 2000. Degree–day factors for snow and ice for Dokriani Glacier, Garhwal Himalayas. *Journal of Hydrology*, *235*(1-2), pp.1-11.

Singh, S., S. Ghosh, A. S. Sahana, H. Vittal, and S. Karmakar, 2017. Do dynamic regional models add value to the global model projections of Indian monsoon? Clim Dyn, 48, 1375–1397, doi:10.1007/s00382-016-3147-y.

Shen, M., Chen, J., Zhuan, M., Chen, H., Xu, C.Y. and Xiong, L., 2018. Estimating uncertainty and its temporal variation related to global climate models in quantifying climate change impacts on hydrology. *Journal of Hydrology*, *556*, pp.10-24.

Shrestha, M., Wang, L., Koike, T., Xue, Y., and Hirabayashi, Y., 2012. Modeling the spatial distribution of snow cover in the Dudhkoshi Region of the Nepal Himalayas, J. Hydrometeorol., 13, 204–222, doi:10.1175/JHM-D-10-05027.1, 2012

Smitha, P.S., Narasimhan, B., Sudheer, K.P. and Annamalai, H., 2018. An improved bias correction method of daily rainfall data using a sliding window technique for climate change impact assessment. *Journal of Hydrology*, *556*, pp.100-118.

STAHL, K., MOORE, R. D., SHEA, J. M., HUTCHINSON, D. & CANNON, A. J., 2008. Coupled modelling of glacier and streamflow response to future climate scenarios. *Water Resources Research,* 44.

Tatsumi, K., T. Oizumi, and Y. Yamashiki, 2014. Assessment of future precipitation indices in the Shikoku region using a statistical downscaling model. Stoch. Env. Res. Risk A., 28(6), 1447–1464, doi:10.1007/s00477-014-0847-x.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012. An overview of CMIP5 and the experiment design. B. Am. Meteorol. Soc., 93(4), 485-498, doi:10.1175/BAMS-D-11-00094.1.

TEUTSCHBEIN, C. & SEIBERT, J., 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology,* 456**,** 12-29.

TROIN, M., VELAZQUEZ, J. A., CAYA, D. & BRISSETTE, F., 2015. Comparing statistical post-processing of regional and global climate scenarios for hydrological impacts assessment: A case study of two Canadian catchments. *Journal of Hydrology,* 520**,** 268-288.

USGS (US Geological Survey) ***1996***a HYDRO 1K Elevation Derivative Database. Earth Resources Observation and Science (EROS) Data Center (EDC), Sioux Falls, South Dakota, USA. http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30/hydro.

USGS (US Geological Survey) ***1996***b GTOPO30 (Global 30 Arc- Second Elevation Data Set). Earth Resources observation and Science (EROS) Data Center (EDC), Sioux Falls, South Dakota, USA. http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30.

Vetter, T., Reinhardt, J., Flörke, M., van Griensven, A., Hattermann, F., Huang, S., Koch, H., Pechlivanidis, I.G., Plötner, S., Seidou, O. and Su, B., 2017. Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. *Climatic change*, *141*(3), pp.419-433.

Vincent, C., Ramanathan, A., Wagnon, P., Dobhal, D.P., Linda, A., Berthier, E., Sharma, P., Arnaud, Y., Azam, M.F. and Gardelle, J., 2013. Balanced conditions or slight mass gain of glaciers in the Lahaul and Spiti region (northern India, Himalaya) during the nineties preceded recent mass loss. The Cryosphere, 7(2), pp.569-582.

Viste, E., and Sorteberg, A. 2015. Snowfall in the Himalayas: an uncertain future from a little-known past. The Cryosphere Discussions, 9, 441-493.

Wagnon, P., Linda, A., Arnaud, Y., Kumar, R., Sharma, P., Vincent, C., Pottakkal, J.G., Berthier, E., Ramanathan, A., Hasnain, S.I. and Chevallier, P., 2007. Four years of mass balance on Chhota Shigri Glacier, Himachal Pradesh, India, a new benchmark glacier in the western Himalaya. *Journal of Glaciology*, *53*(183), pp.603-611.

WIDEN-NILSSON, E., GONG, L., HALLDIN, S. & XU, C. Y. 2009. Model performance and parameter behavior for varying time aggregations and evaluation criteria in the WASMOD-M global water balance model. *Water Resources Research,* 45.

Wilby, R. L., and C. W. Dawson, 2013. The statistical downscaling model: insights from one decade of application. Int. J. Climatol., 33(7), 1707–1719, doi:10.1002/joc.3544.

Wilby R L, Dawson C W, Barrow E M., 2002. DBC - a decision support tool for the assessment of regional climate change impacts. Environmental Modelling & Software, 17(2):145-157.

Winiger, M. G. H. Y., Gumpert, M., & Yamout, H., 2005. Karakorum–Hindukush–western Himalaya: assessing high-altitude water resources. Hydrological Processes, 19(12), 2329-2338.

Xu, C-Y., 2002. WASMOD - The Water And Snow balance MODelling system. *In:* SINGH, V. P. & FREVERT, D. K. (eds.) *Mathematical Models of Small Watershed Hydrology and Applications.* LLC,Chelsea, Michigan, USA: Water Resources Publications.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N. and Kitoh, A., 2012. APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *Bulletin of the American Meteorological Society*, *93*(9), pp.1401-1415.

Table 1. Daily GSM-WASMOD equations and parameters

Variable controlled	Parameter (units)	Equation	
WASMOD-D module			
Snow fall	a_1, a_2(°C)	$s_t = p_t\left\{1-\exp\left(-\left(\left\{(T_a-a_1)/(a_1-a_2)\right\}^-\right)^2\right)\right\}^+$	(1)
Rainfall		$r_t = p_t - s_t$	(2)
Snow storage		$sp_t = sp_{t-1} + s_t - m_t$	(3)
Snow melt		$m_t = sp_t \cdot \left\{1-\exp\left(-\left(\left((a_2-T_a)/(a_1-a_2)\right)^-\right)^2\right)\right\}^+$	(4)
Actual evapotranspiration	a_4(-)	$e_t = \min[ep_t(1-a_4{}^{w_t/ep_t}), w_t]$	(5)
Available water		$w_t = r_t + sm_{t-1}^+$	(6)
Saturated percentage area	c_1(-)	$sp_t = 1 - e^{-c_1 w_t}$	(7)
Fast flow		$s_t = (r_t + m_t) \cdot sp_t$	(8)
Slow flow	c_2(mm^{-1}day)	$f_t = w_t\left(1-e^{-c_2 w_t}\right)$	(9)
Total flow		$d_t = s_t + f_t$	(10)
Land moisture		$sm_t = sm_{t-1} + r_t + m_t - e_t - d_t$	(11)
Glacier and snow (GSM) module			
Glacier and snow mass gain	T_s(°C), ΔT(K)	$G_t = \begin{cases} p_t & \forall T_a \le T_s - \Delta T/2 \\ p_t \cdot \left[(T_s - T_a)/\Delta T + 0.5\right] & \forall T_s - \Delta T/2 < T_a < T_s + \Delta T/2 \\ 0 & \forall T_a \ge T_s + \Delta T/2 \end{cases}$	(12)
Glacier and snow mass melt	*DDF*	$M_{s/f/i} = \max\left(DDF_{s/f/i}\left(T_a - T_0\right), 0\right)$	(13)

where {x}+ means max(x,0) and {x}- means min(x,0); ep_t *is the daily potential evapotranspiration;* a_1 *is the snowfall temperature and* a_2 *is the snow melt temperature;* T_a *is air temperature(°C); p_t is the precipitation in a given day;* sm_{t-1} *is the land moisture (a available storage;* T_S *is a threshold temperature for snow distinguishes between rain and snow* T_S *= 1 °C ;* ΔT *is a temperature interval,* ΔT = *2 K; DDF_s , DDF_f and DDF_i are the degree day factor for snow, firn and ice, and* T_0 *is the melt threshold factor in GSM module.*

Table 2. Climate change scenarios for Beas river basin at the 21st Century (2046-2065 and 2080-2099)

Statistical Downscaling	RCP	GCMs	Abbreviation	Description
DBC	4.5	CamESM2	CA2	Wet&Cold
DBC	8.5	CSIRO_Mk3_6_0	CS0	
LOCI	4.5	CamESM2	CA2	
LOCI	8.5	CSIRO_Mk3_6_0	CS0	
DBC	4.5	Inmcm4	IN4	Dry&Cold
DBC	8.5	MRI-ESM1	MR1	
LOCI	4.5	Inmcm4	IN4	
LOCI	8.5	MRI-ESM1	MR1	
DBC	4.5	IPSL-CM5A-LR	IPR	Dry&Warm
DBC	8.5	IPSL_CM5A_LR	IPR	
LOCI	4.5	IPSL-CM5A-LR	IPR	
LOCI	8.5	IPSL_CM5A_LR	IPR	
DBC	4.5	MRI_CGCM3	MR3	Wet&Warm
DBC	8.5	MIROC5	MI5	
LOCI	4.5	MRI_CGCM3	MR3	
LOCI	8.5	MIROC5	MI5	

Table 3. The average winter precipitation (DJFM) of WRF and Gauge at different altitudes

Altitude (m a.m.s.l.)	>2000	>3000	>4000	>4800	>6000
Area (%)	88%	62%	41%	21%	1%
Gauge	279.3	279.7	278.7	279.0	278.9
WRF	629.2	725.9	762.3	746.4	628.7
WRF/Gauge	2.25	2.59	2.74	2.67	2.25

Table 4. Calibration (1986-2000) and validation (1999-2004) of simulated glacier mass balance in Beas river basin comparing with the data from previous studies

Unit: m w.e. a^{-1}	1986-2000	1999-2004	Methods
GSM-WASMOD	-0.22	-1.09	model
Azam et al. (2014)	-0.01(-/+0.36)	/	model
Engelhardt et al. (2017)	-0.29 (-/+033)	-0.8(-/+0.33)	model
Berthier et al. (2007)	/	-1.02 /-1.12*	Geodetic measurement
Vincent et al. (2013)	/	-1.03 (-/+0.44)	Geodetic measurement

**: from different assumptions*

Table 5. Calibration (1986-2000) and validation (2001-2004) of WASMOD and GSM-WASMOD based on uncorrected and corrected precipitation.

		Calibration (1986-2000)				Validation (2001-2004)			
Model	Precipitation	NSC_d	NSC_m	VE	RMSE	NSC_d	NSC_m	VE	RMSE
WASMOD	Corrected	0.50	0.65	5%	2.40	0.31	0.36	28%	2.62
GSM-WASMOD	Uncorrected	0.64	0.70	8%	2.03	0.49	0.52	28%	1.94
GSM-WASMOD	Corrected	0.65	0.75	7%	2.01	0.61	0.66	15%	1.71

NSC_d: daily Nash-Sutcliffe coefficient; NSC_m: monthly Nash-Sutcliffe coefficient

Table 6. Annual mean change (including the mean, minimum and maximum values) of main hydrological variables over Beas river basin under future climate comparing with the historical periods.

Period	RCP	Glacier loss (%)*	dP (%)	dT (°C)	dET (%)	dQ (%)
2046-2065	RCP4.5	73(63/81)	9.8(-11.5/29.9)	1.8(0.8/2.7)	72.4(36.5/116.6)	2.6(-19.9/23.9)
	RCP8.5	81(76/87)	33.3 (5.3/68.1)	2.8(2.3/3.8)	86.7(13.4/161)	25.3(-6.5/58)
2080-2099	RCP4.5	94(89/99)	17.7(6.4/39.4)	2.3(1.2/3.3)	82(18.7/139.1)	8.9(-2.2/32.2)
	RCP8.5	99(93/100)	39.7(-18.5/89.1)	5.4(4.2/7.2)	145(50.9/274.4)	27(-40.6/84.9)

dP: the changes of precipitation; dT: the changes of temperature; dET: the changes of ET; dQ: the changes of runoff

**: Comparing with baseline glacier extent, the future glacier cover loss at the end of 2050 and 2099 in the table, which is respect to 2046-2065 and 2080-2099, respectively.*

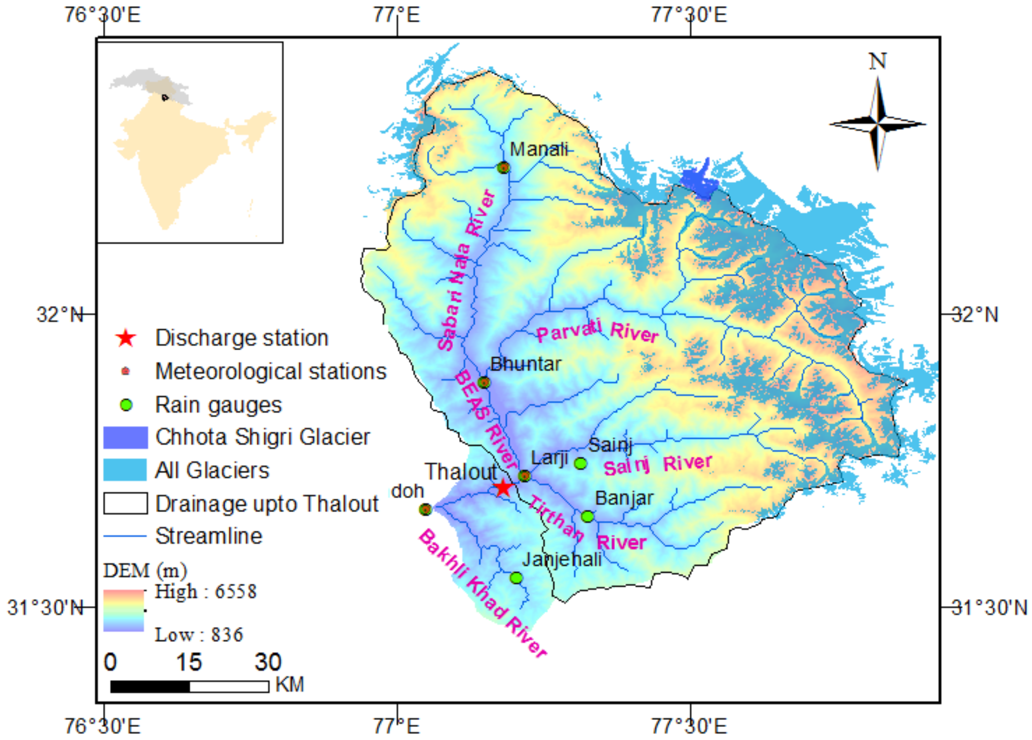

Fig. 1 The topography, stream network and glacier cover of Beas river basin up to Pandoh dam with seven rain gauges and Thalout discharge station (The small figure on the upper right corner shows the location of Beas river basin up to Pandoh within Upper Indus Basin (UIB) region and India).

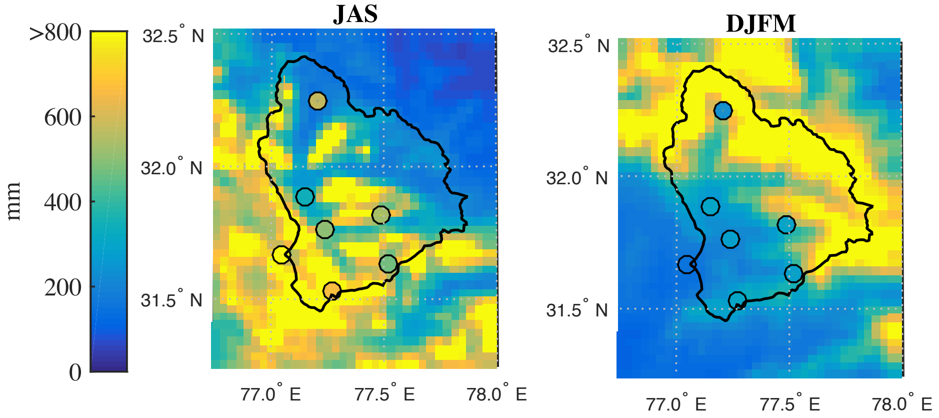

Fig. 2 Seasonal precipitation (1998-2005) from 3km WRF (from Li et al., 2017) and Gauge (dot) in Beas River basin.

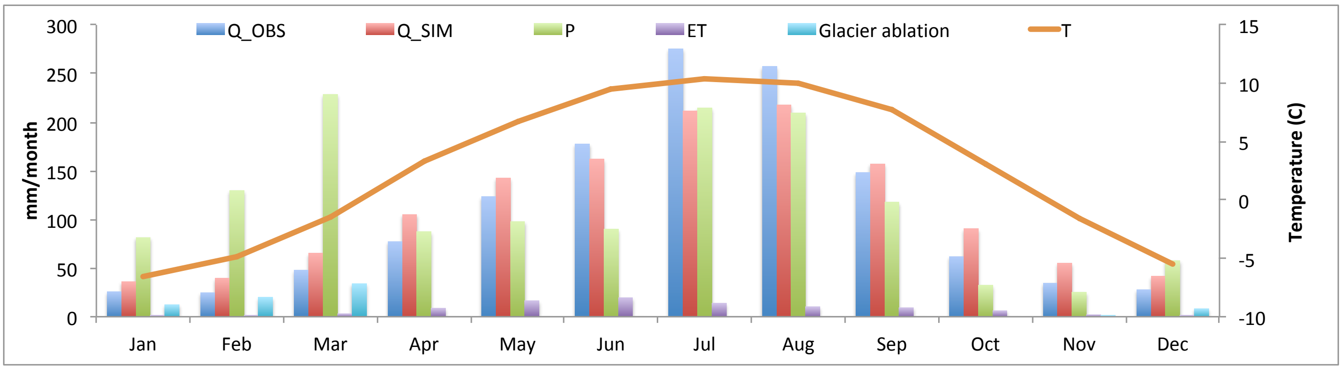

Fig. 3 Monthly mean of the water balance terms and temperature for the Beas river basin (1986-2004), which shows observed discharge (Q_OBS), simulated discharge (Q_SIM), precipitation (P), evaporation (ET), glacier ablation (in the primary axis on the left side) and temperature (T) (in the secondary axis on right side).

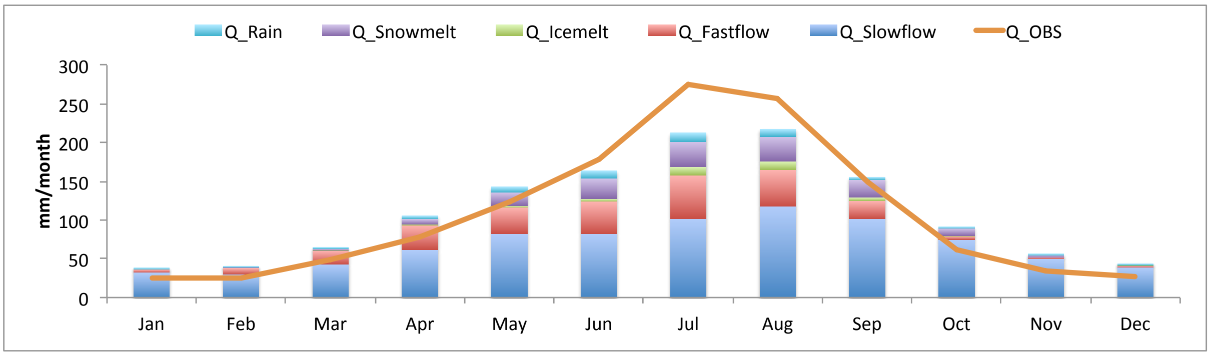

Fig. 4 the Mean monthly observed discharge (Q_OBS) and the components of simulated discharge in Beas river basin (1990-2004), including fast flow (Q_fastflow), slow flow (Q_slowflow) from non-glacier area and discharges from glacier area, which includes rainfall discharge (Q_Rain), snow-melt (Q_Snowmelt) and ice-melt (Q_icemelt) discharge.

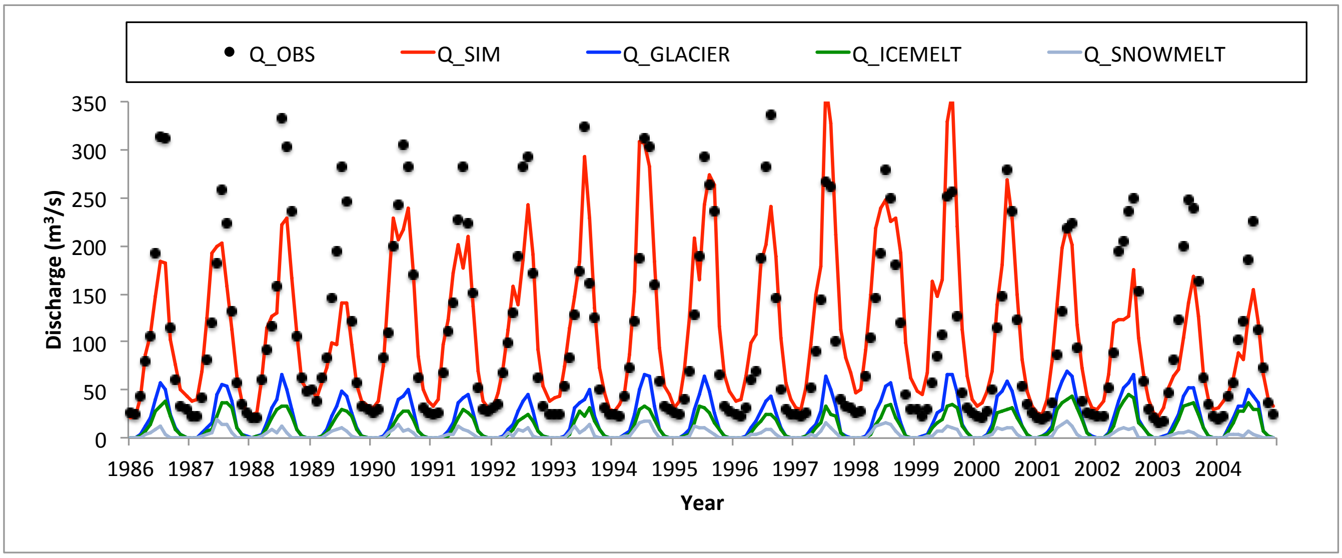

Fig. 5 Monthly hydrograph of the observed (Q_OBS) and simulated discharge (Q_SIM), total discharge from glacier (Q_GLACIER), ice melting (Q_ICEMELT) and snow melting discharge (Q_SNOWMELT) in Beas river basin during 1986-2004.

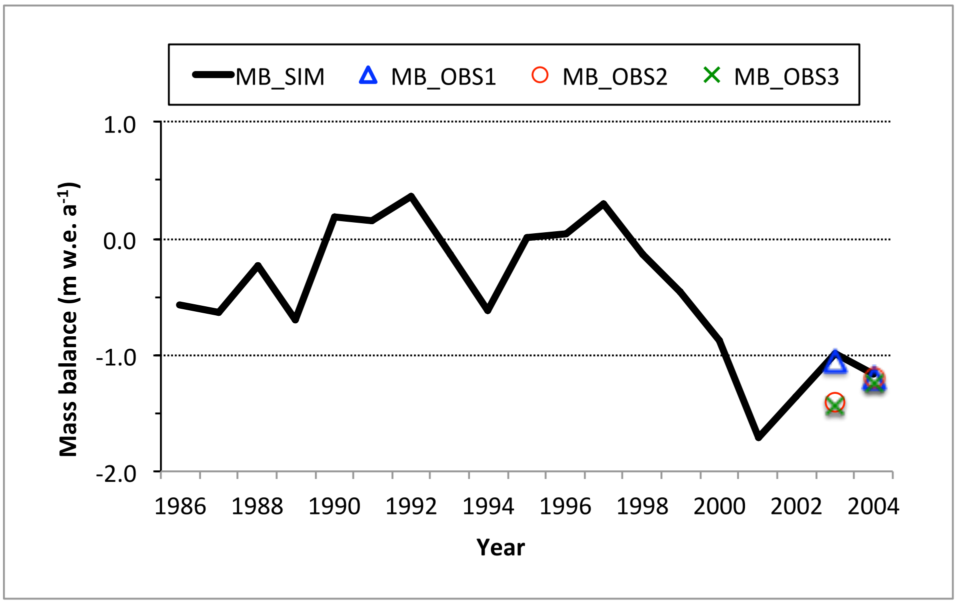

Fig. 6 The simulated glacier mass balance (MB_OBS) in Beas River basin during 1986-2004 and observed Chhota Shigri glacier mass balance, i.e., MB_OBS1 (Berthier et al., 2007), MB_OBS2 (Wagnon et al., 2007), and MB_OBS3 (Azam et al., 2016).

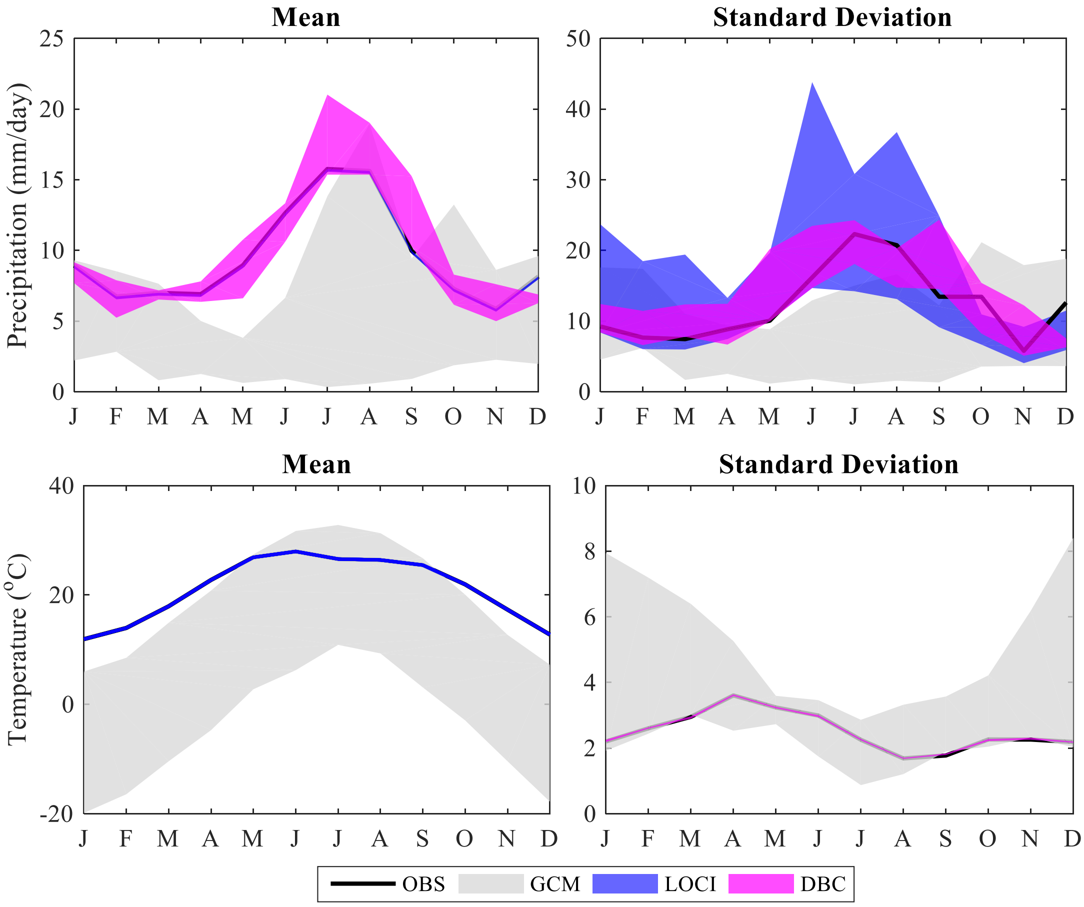

Fig. 7 Monthly means and standard deviations of daily precipitation (upper panel) and temperature (down panel) from observation (OBS), climate models (GCM) and downscaling of climate models (LOCI and DBC) at Pandoh station in 1986-2005. The envelope represents the results of multiple model ensemble.

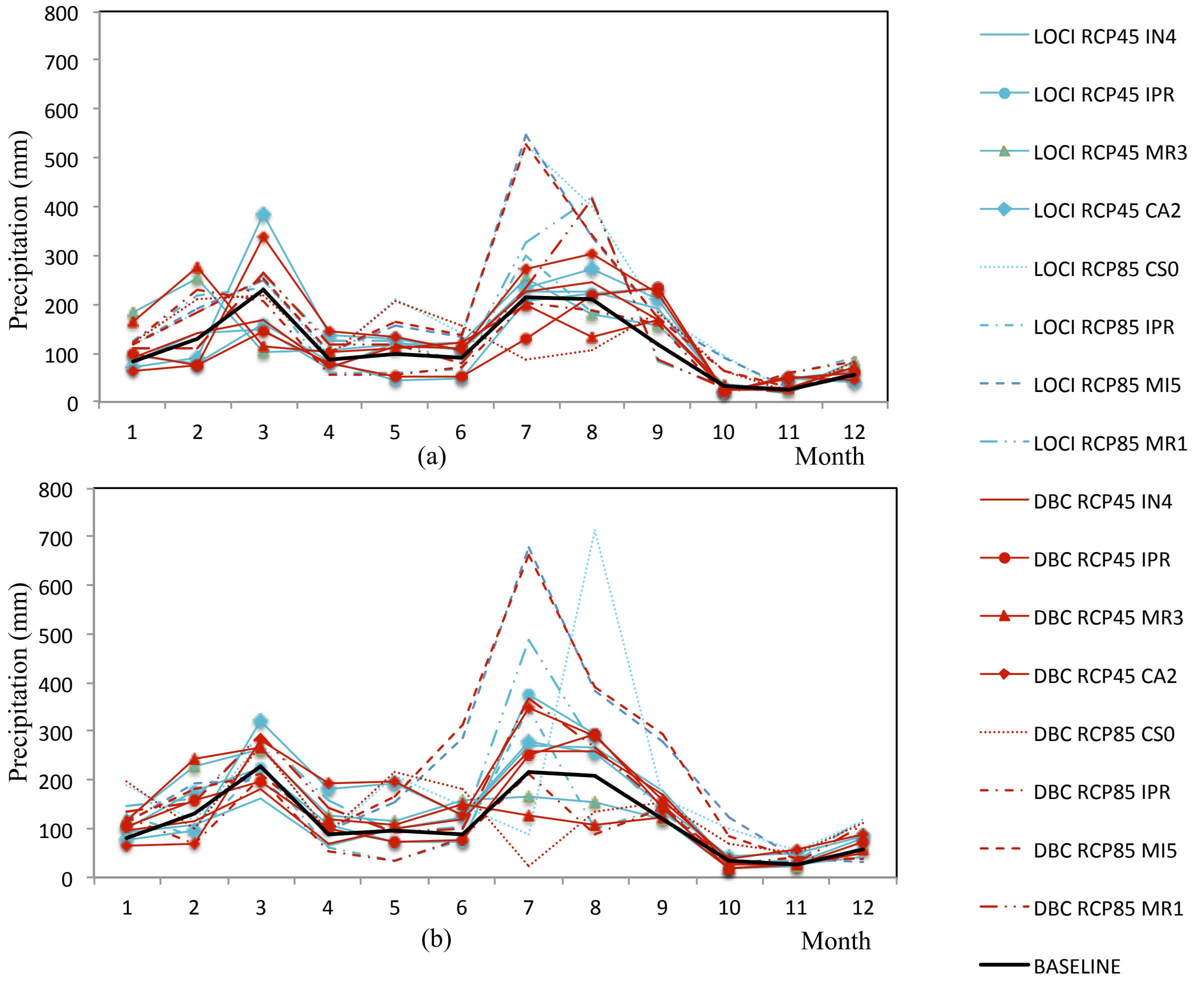

Fig. 8 Average monthly mean observed (Baseline of 1986-2005) and simulated precipitation based on two bias correction methods under climate change scenarios from two ensembles of four GCMs over Beas river basin during (a) 2046-2065, (b) 2080-2099.

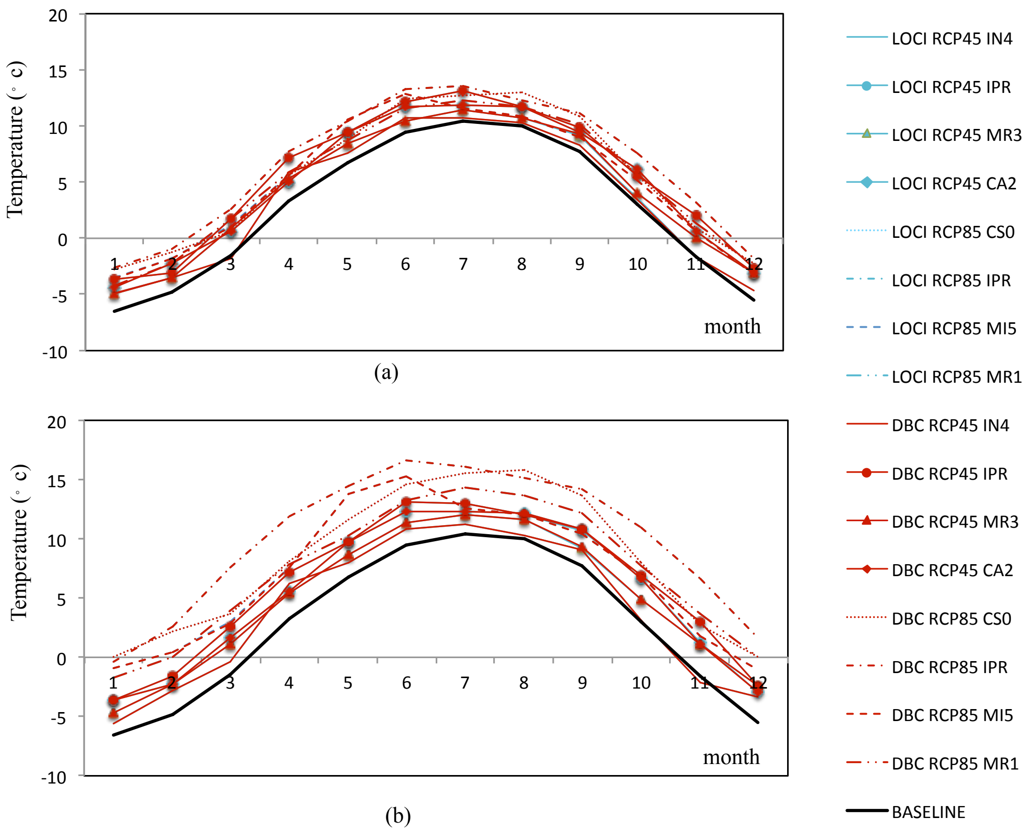

Fig. 9 Average monthly mean observed (Baseline of 1986-2005) and simulated temperature based on two bias correction methods under climate change scenarios from two ensembles of four GCMs over Beas river basin during (a) 2046-2065, (b) 2080-2099.

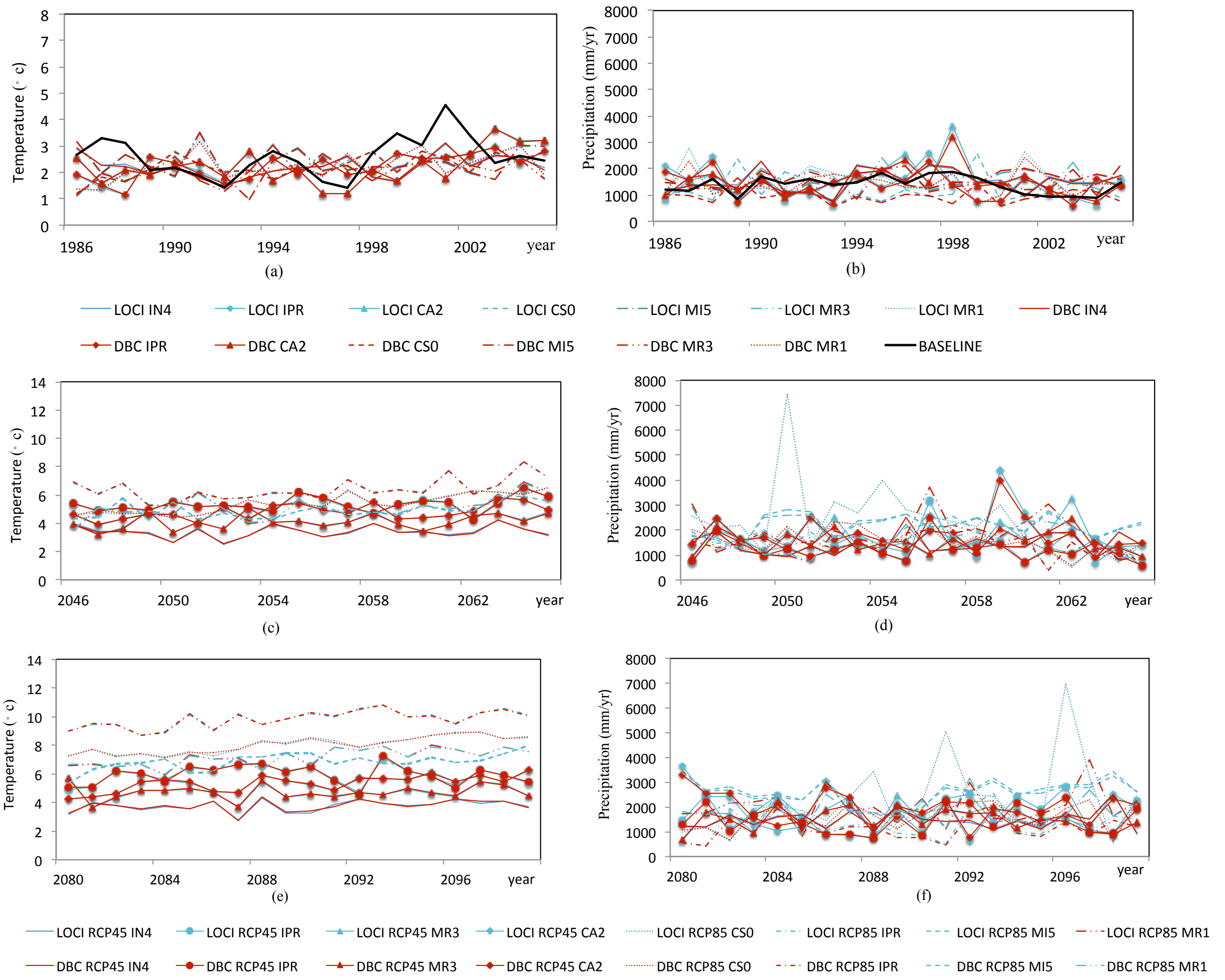

Fig. 10 The average annual temperature and precipitation based on two bias correction methods under climate change scenarios from two ensembles of four GCMs, including RCP45 and RCP84, over the Beas river basin during 1986-2005, 2046-2065 and 2080-2099.

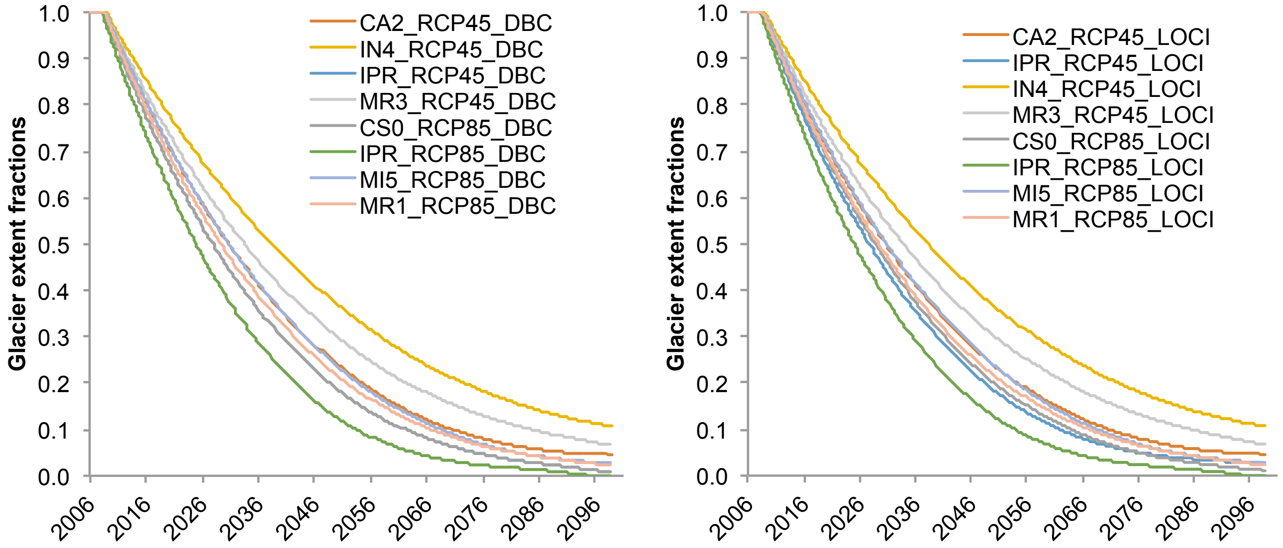

Fig. 11 Projected changes of glacier extent for Beas river basin during 21st century.

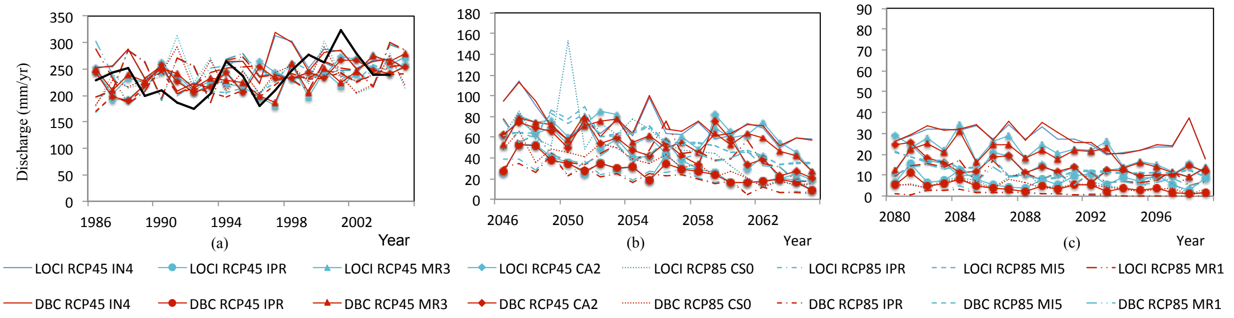

Fig. 12 Glacier discharge from LOCI and DBC under scenarios from two ensembles of four GCMs including RCP4.5 and RCP8.5 over Beas river basin during (a) 1986-2005, (b) 2046-2065 and (c) 2080-2099. The back line in sub-figure (a) represents the baseline glacier discharge in historical period with the corrected precipitation (please note the scales change of Y-axis in three sub-figures).

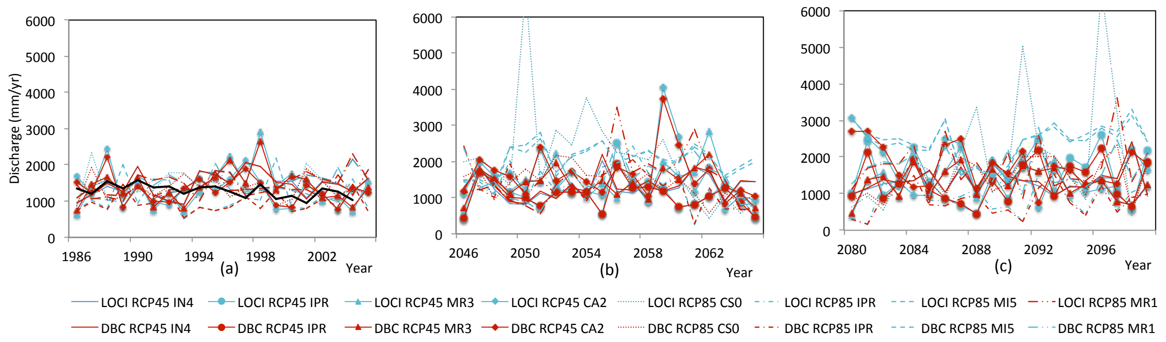

Fig. 13 Total discharge from LOCI and DBC under scenarios from two ensembles of four GCMs including RCP4.5 and RCP8.5 over Beas river basin during (a) 1986-2005, (b) 2046-2065 and (c) 2080-2099. The back line in sub-figure (a) represents the baseline discharge in historical period with the corrected precipitation.

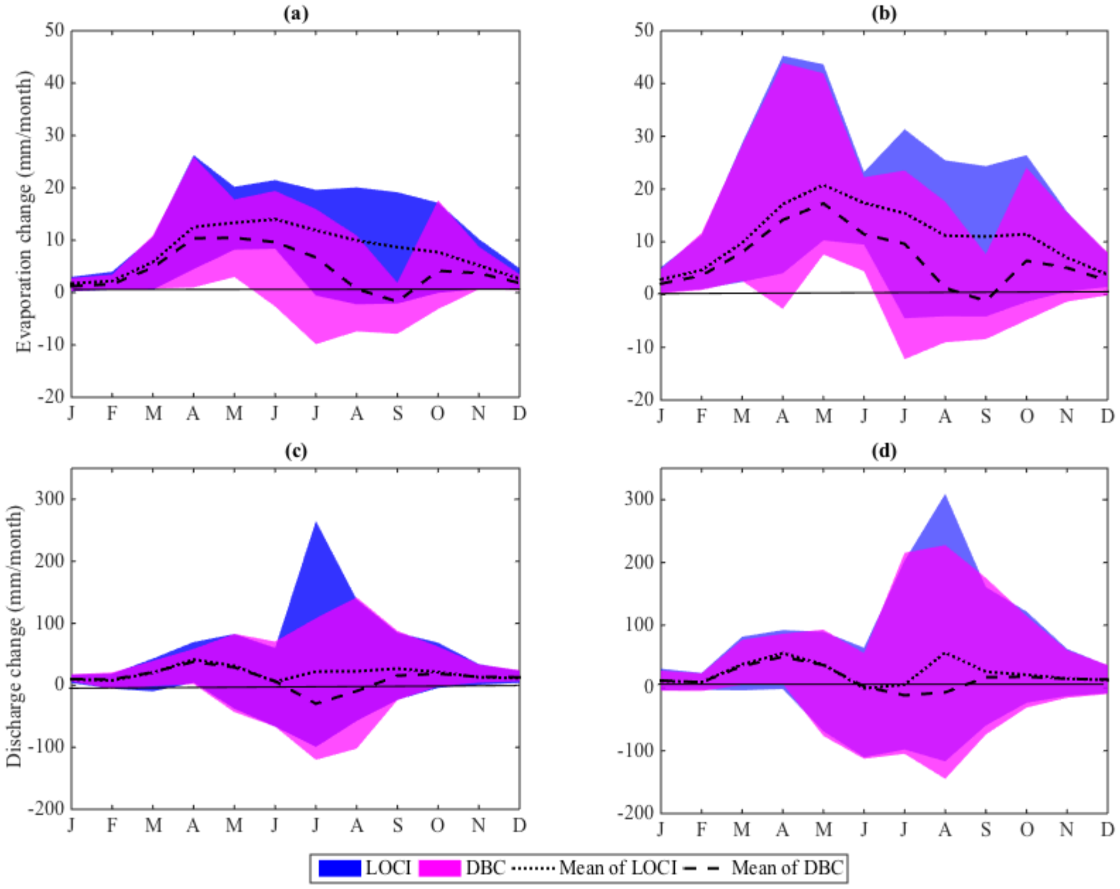

Fig. 14 Changes of mean monthly evaporation (upper panel) and discharge (down panel) over Beas river basin for the middle of the century (2045-2055) (left panel) and the end of the century (2080-2099) (right panel) comparing with the baseline period (1986-2005). The envelope represents the results of multiple model ensemble.

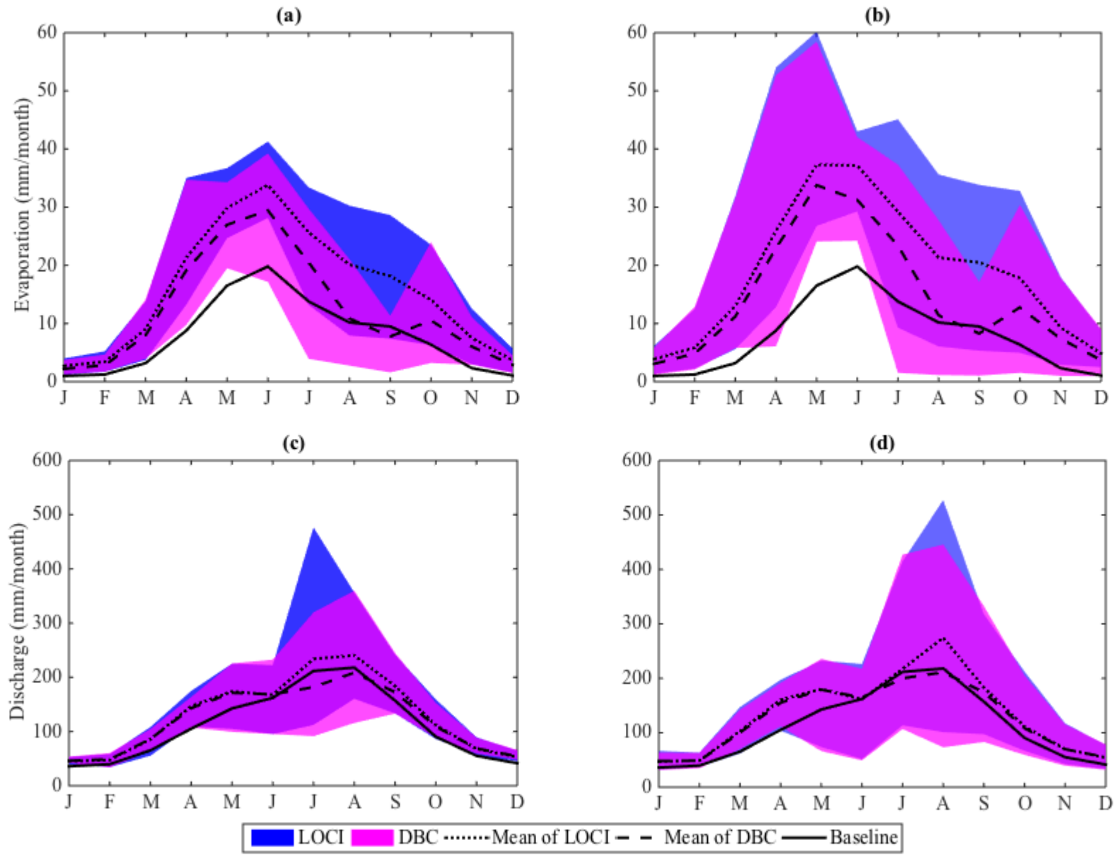

Fig. 15 The mean monthly evaporation (upper panel) and discharge (down panel) over Beas river basin for the middle of the century (2045-2055) (left panel) and the end of the century (2080-2099) (right panel) comparing with the baseline (1986-2005). The envelope represents the results of multiple model ensemble.